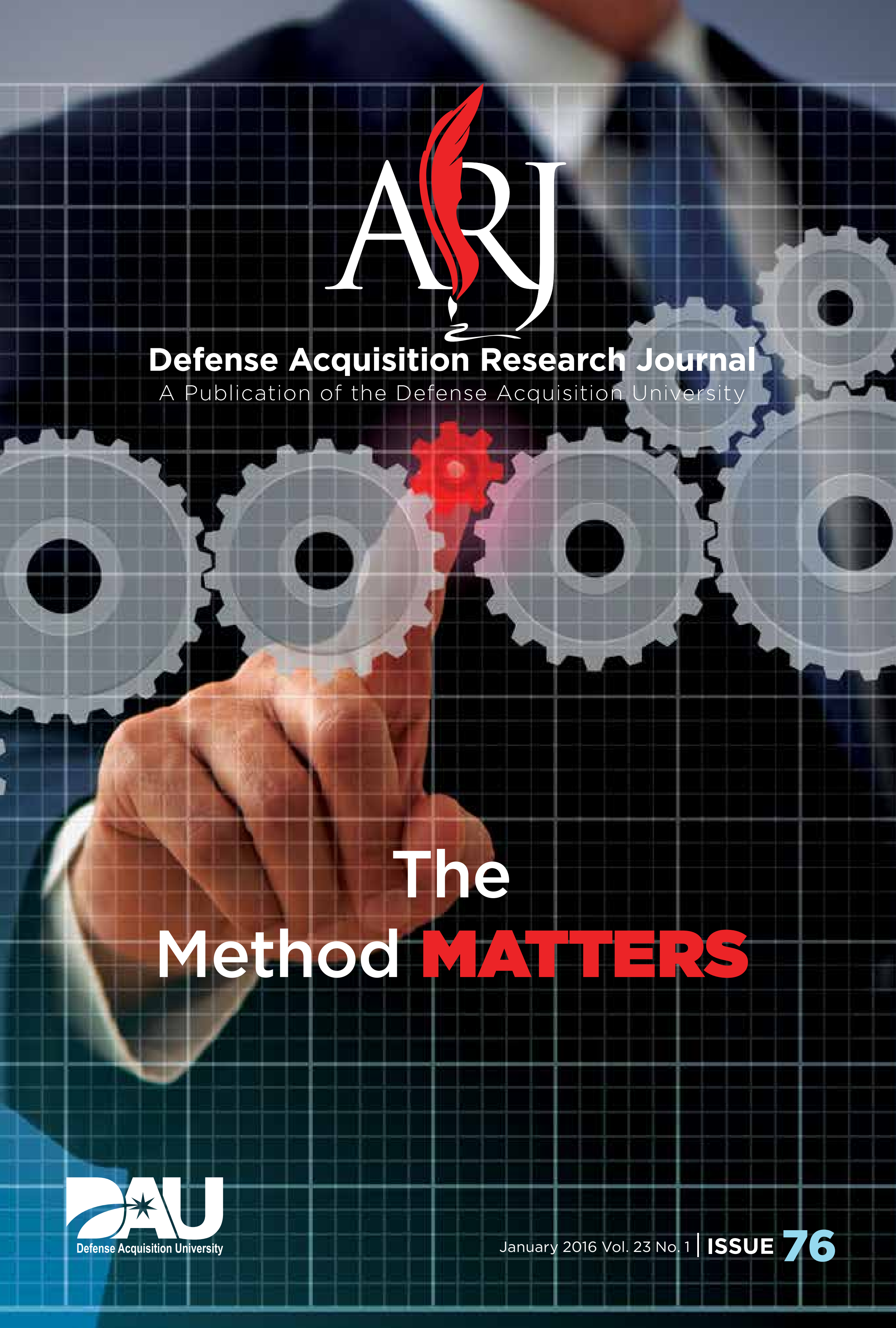

ARJ

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The Method MATTERS

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Article List

ARJ Extra

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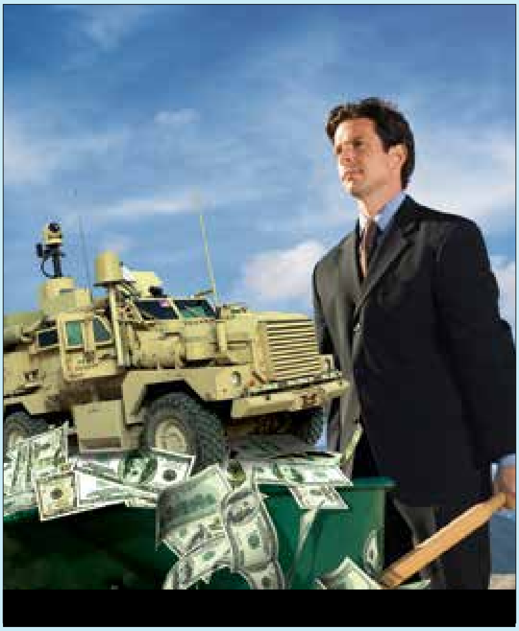

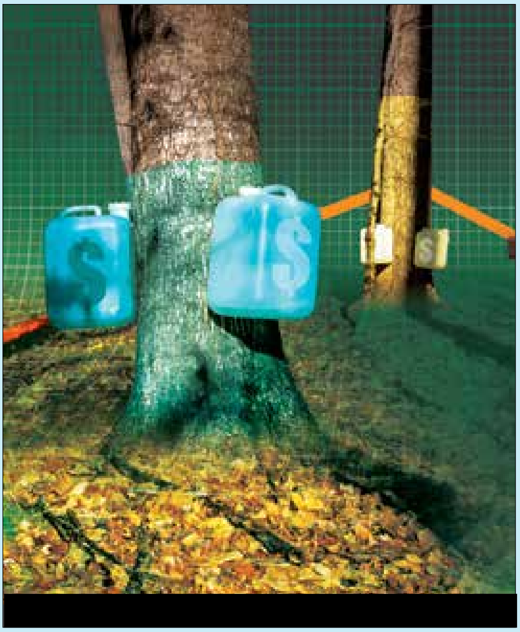

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Tapping Transaction Costs to Forecast Acquisition Cost Breaches

Laura E. Armey and Diana I. Angelis

Transaction costs are estimated using Systems Engineering and Program Management (SE/PM) costs as a share of total costs; survival analysis is then used to predict whether such costs influence the likelihood of cost breaches.

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Human Systems Engineering and Program Success—A Retrospective Content Analysis

Liana Algarín

This article describes the use of retrospective content analysis to examine documents from Major Defense Acquisition Programs. The outcome demonstrates the impact of implementation of Human Systems Integration on system development life-cycle cost and schedule.

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FROM THE CHAIRMAN AND EXECUTIVE EDITOR

Dr. Larrie D. Ferreiro

The theme for this edition of the *Defense Acquisition Research Journal* is "The Method Matters." The lead article is "Survey of Modular Military Vehicles: Benefits and Burdens," by Jean M. Dasch and David J. Gorsich, which goes a long way to defining the often-misunderstood word "modularity" and provides a balanced look at the benefits and drawbacks of this acquisition methodology. Acquisition methodology is also at the heart of a classic article from the Summer 1995 issue of the *Acquisition Review Quarterly*, entitled "Technology Approach: DoD Versus Boeing (A Comparative Study)," by A. Lee Battershell. The author examines how the market-driven approach to development—where cost and schedule dominate decision making—contrasts with the military's performance-driven approach and how each one can affect development time.

"Tapping Transaction Costs to Forecast Acquisition Cost Breaches," by Laura E. Armey and Diana I. Angelis, highlights an intriguing method to predict program cost overruns and breaches by focusing on transaction costs, as measured by proxy indicators of systems engineering and program management costs, as a leading indicator. Finally, "Human Systems Engineering and Program Success—A Retrospective Content Analysis," by Liana Algarín, describes the

impact of early identification and assessment of human systems integration requirements on the development life-cycle costs and schedules of acquisition programs.

Please note the updates to the DAU Research Agenda 2016–2017. Based upon Better Buying Power 3.0, in the area of "Competition" we have added a substantial section titled "Improve DoD Outreach for Technology and Products from Global Markets." As always, the full agenda is intended to make researchers aware of the topics that are, or should be, of particular concern to the broader defense acquisition community within the federal government, academia, and industrial sectors. To view the agenda in its entirety, visit http://www.dau.mil/research/Pages/researchareas.aspx.

The astute reader will note changes to our masthead. Richard T. Ginman, Andre J. Gudger, Dr. Ned Kock, and James E. Thomsen have all moved on to other endeavors, and we wish them well. On the other hand, we are pleased to welcome David Gallop to our editorial board.

The featured book in this issue's Defense Acquisition Professional Reading List is *To Engineer is Human: The Role of Failure in Successful Design*, by Henry Petroski. This book is frequently cited by *Defense AT&L* leadership as one of the more influential works. We are grateful to Dr. Petroski for graciously contributing a summary of the book in his own words.

DAU CENTER FOR DEFENSE ACQUISITION

RESEARCH AGENDA 2016–2017

This Research Agenda is intended to make researchers aware of the topics that are, or should be, of particular concern to the broader defense acquisition community within the federal government, academia, and defense industrial sectors. The center compiles the agenda annually, using inputs from subject matter experts across those sectors. Topics are periodically vetted and updated by the DAU Center's Research Advisory Board to ensure they address current areas of strategic interest.

The purpose of conducting research in these areas is to provide solid, empirically based findings to create a broad body of knowledge that can inform the development of policies, procedures, and processes in defense acquisition, and to help shape the thought leadership for the acquisition community. Most of these research topics were selected to support the DoD's Better Buying Power Initiative (see http://bbp.dau.mil). Some questions may cross topics and thus appear in multiple research areas.

Potential researchers are encouraged to contact the DAU Director of Research (research@dau.mil) to suggest additional research questions and topics. They are also encouraged to contact the listed Points of Contact (POC), who may be able to provide general guidance as to current areas of interest, potential sources of information, etc.

Competition POCs

- John Cannaday, DAU: john.cannaday@dau.mil
- Salvatore Cianci, DAU: salvatore.cianci@dau.mil
- Frank Kenlon (global market outreach), DAU: frank.kenlon@dau.mil

Measuring the Effects of Competition

- What means are there (or can be developed) to measure the effect on defense acquisition costs of maintaining the defense industrial base in various sectors?
- What means are there (or can be developed) of measuring the effect of utilizing defense industrial infrastructure for commercial manufacture, and in particular, in growth industries? In other words, can we measure the effect of using defense manufacturing to expand the buyer base?
- What means are there (or can be developed) to determine the degree of openness that exists in competitive awards?
- What are the different effects of the two best value source selection processes (tradeoff vs. lowest price technically acceptable) on program cost, schedule, and performance?

Strategic Competition

- Is there evidence that competition between system portfolios is an effective means of controlling price and costs?
- Does lack of competition automatically mean higher prices? For example, is there evidence that sole source can result in lower overall administrative costs at both the government and industry levels, to the effect of lowering total costs?
- What are the long-term historical trends for competition guidance and practice in defense acquisition policies and practices?

- To what extent are contracts being awarded noncompetitively by congressional mandate for policy interest reasons? What is the effect on contract price and performance?

- What means are there (or can be developed) to determine the degree to which competitive program costs are negatively affected by laws and regulations such as the Berry Amendment, Buy America Act, etc.?

- The DoD should have enormous buying power and the ability to influence supplier prices. Is this the case? Examine the potential change in cost performance due to greater centralization of buying organizations or strategies.

Effects of Industrial Base

- What are the effects on program cost, schedule, and performance of having more or fewer competitors? What measures are there to determine these effects?

- What means are there (or can be developed) to measure the breadth and depth of the industrial base in various sectors that go beyond simple head-count of providers?

- Has change in the defense industrial base resulted in actual change in output? How is that measured?

Competitive Contracting

- Commercial industry often cultivates long-term, exclusive (noncompetitive) supply chain relationships. Does this model have any application to defense acquisition? Under what conditions/circumstances?

- What is the effect on program cost, schedule, and performance of awards based on varying levels of competition: (a) “Effective” competition (two or more offers); (b) “Ineffective” competition (only one offer received in response to competitive solicitation); (c) split awards vs. winner take all; and (d) sole source.

Improve DoD Outreach for Technology and Products from Global Markets

- How have militaries in the past benefitted from global technology development?
- How/why have militaries missed the largest technological advances?
- What are the key areas that require the DoD's focus and attention in the coming years to maintain or enhance the technological advantage of its weapon systems and equipment?
- What types of efforts should the DoD consider pursuing to increase the breadth and depth of technology push efforts in DoD acquisition programs?
- How effectively are the DoD's global science and technology investments transitioned into DoD acquisition programs?
- Are the DoD's applied research and development (i.e., acquisition program) investments effectively pursuing and using sources of global technology to affordably meet current and future DoD acquisition program requirements? If not, what steps could the DoD take to improve its performance in these two areas?
- What are the strengths and weaknesses of the DoD's global defense technology investment approach as compared to the approaches used by other nations?
- What are the strengths and weaknesses of the DoD's global defense technology investment approach as compared to the approaches used by the private sector—both domestic and foreign entities (companies, universities, private-public partnerships, think tanks, etc.)?
- How does the DoD currently assess the relative benefits and risks associated with global versus U.S. sourcing of key technologies used in DoD acquisition programs? How could the DoD improve its policies and procedures in this area to enhance the benefits of global technology sourcing while minimizing potential risks?

- How could current DoD/U.S. Technology Security and Foreign Disclosure (TSFD) decision-making policies and processes be improved to help the DoD better balance the benefits and risks associated with potential global sourcing of key technologies used in current and future DoD acquisition programs?

- How do DoD primes and key subcontractors currently assess the relative benefits and risks associated with global versus U.S. sourcing of key technologies used in DoD acquisition programs? How could they improve their contractor policies and procedures in this area to enhance the benefits of global technology sourcing while minimizing potential risks?

- How could current U.S. Export Control System decision-making policies and processes be improved to help the DoD better balance the benefits and risks associated with potential global sourcing of key technologies used in current and future DoD acquisition programs?

Comparative Studies

- Compare the industrial policies of military acquisition in different nations and the policy impacts on acquisition outcomes.

- Compare the cost and contract performance of highly regulated public utilities with nonregulated "natural monopolies," e.g., military satellites, warship building, etc.

- Compare contracting/competition practices between the DoD and complex, custom-built commercial products (e.g., offshore oil platforms).

- Compare program cost performance in various market sectors: highly competitive (multiple offerors), limited (two of three offerors), monopoly?

- Compare the cost and contract performance of military acquisition programs in nations having single "purple" acquisition organizations with those having Service-level acquisition agencies.

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Survey of **Modular Military Vehicles:** BENEFITS and BURDENS

Jean M. Dasch and David J. Gorsich

Modularity in military vehicle design is generally considered a positive attribute that promotes adaptability, resilience, and cost savings. The benefits and burdens of modularity are considered by studying historical programs dating back to World War II. Using a taxonomy developed at the U.S. Army Tank Automotive Research, Development and Engineering Center, vehicles were considered based on horizontal modularity, vertical modularity, and distributed modularity. Examples were given for each type, including the most extensive attempt at horizontal modularity in the 1980s, known as the Armored Family of Vehicles. Following these examples, various cost/benefit studies over the life cycle of the vehicle are reviewed with differing conclusions depending on the initial assumptions. Finally, a number of design factors are included that should be considered in any program on modular vehicles, as well as some recent initiatives that guide the path forward.

Keywords: *military vehicles, modularity, modular, armored family of vehicles (AFV), cost benefit*

lead image by Diane Fleischer

Modularity and adaptability are considered desirable, cost-saving attributes for military vehicles. Army Chief of Staff Raymond Odierno has stated that, "We need to become more agile, adaptable, and responsive to a wide variety" of threats (Ackerman, 2011, para. 9). Modularity also corresponds with an Army definition of a resilient system as one that "is easily adapted to many others through reconfiguration or replacement" (Holland, 2013, p. 3). Finally, the expected cost benefits fit well with the DoD initiative promoting Better Buying Power, which emphasizes the need for Modular Open Systems Architecture in program planning.

But the definition of modularity can cover a large design range. On one end of the spectrum, the purpose of modularity is to lower costs by using common components or a common chassis over a number of vehicle variants. On the other end of the spectrum, modular vehicles are those that can be interchanged in theater to accomplish different purposes. Thus, modularity may have different end states/cost savings due to commonality or greater operational flexibility to perform multiple missions.

Past attempts at modularity since World War II will be reviewed throughout this article. Historically, modularity usually involved producing variants on a single chassis, defined as horizontal modularity in a subsequent section of this article. Newer attempts at modularity incorporate more ambitious designs that strive for agile and adaptable vehicles. Following the examples, past studies on the benefits and burdens of modularity over a vehicle's life cycle will be reviewed.

The ultimate question of whether a new system should be modularized cannot be answered here due to the many variables at play. However, this article will lay out some of the past successes and failures, and provide design points for consideration. Finally, two current efforts to determine modularity benefits and burdens for specific scenarios will be described—one through a U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC)-sponsored Automotive Research Center (ARC) project, and the other through the Office of Naval Research (ONR).

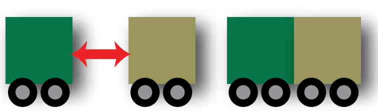
Definitions of Modular Systems

As mentioned earlier, modularity can include a wide range of vehicle platforms that can fulfill a variety of missions. Modular vehicles might be considered the opposite of unique vehicles in which each vehicle is designed and built for a specific purpose. Somewhere between unique and modular

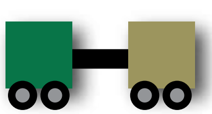
lies the concept of commonality in which different vehicle platforms share common components. Commonality for military equipment was explored by a Rand Corporation study sponsored by the Army Capabilities Integration Center (Held, Newsome, & Lewis, 2008). As expected, commonality was found to be desirable, for it can increase operational flexibility and reduce procurement, logistical, and training burdens. But, perhaps less expected, it can also decrease design freedom and may increase costs due to excess functionality. So it is with modularity—the perceived benefits of modularity can sometimes be offset by the negative aspects.

Prior to discussing the benefits and burdens of modularity, it is necessary to define modularity as used in this article. The Advanced Concepts Team at TARDEC investigated and presented a taxonomy of modular approaches (Iler, 2009) based on ideas developed in the 1990s that guided the thinking during the pre-Future Combat Systems (FCS) era. The three types of modularity in this taxonomy are horizontal, vertical (articulated or not), and distributed (Figure 1). The vertical/horizontal designation refers to the orientation of the mating surface between the modules. The three types of modularity are further described in subsequent sections of this article.

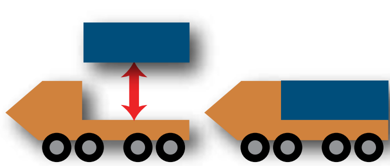
FIGURE 1. TAXONOMY OF MODULAR VEHICLES



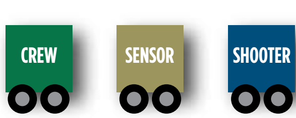
Vertical Modularity: Two vehicle modules merge to create one complete vehicle.



Vertical Modularity/Articulated: Two vehicle modules connected via a powered or unpowered articulated joint to create a complete vehicle.



Horizontal Modularity: Vehicle mission equipment installed in chassis to create a complete vehicle.



Distributed Modularity: Vehicle functions distributed among a series of manned and robotic platforms connected via C41 network.

Source: Iler, 2009
Note. C4I = Command, Control, Communications, Computers, and Intelligence.

Horizontal Modularity (Family of Vehicles)

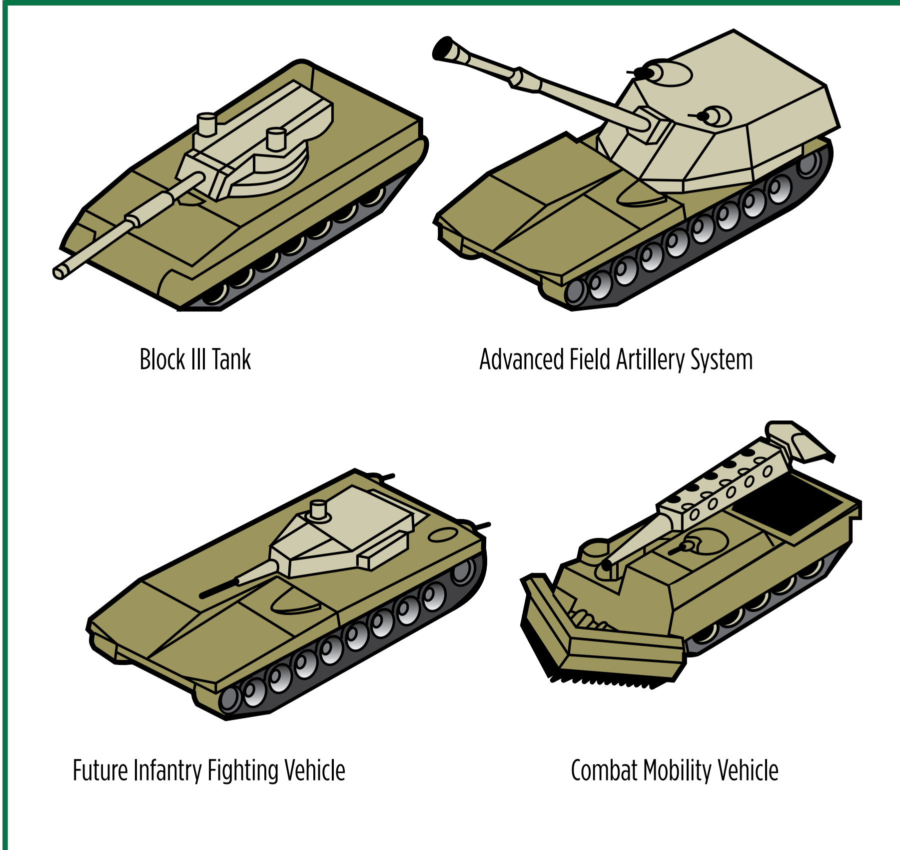
By far the most common form of modularity to date is that of horizontal modularity, also described as a Family of Vehicles (FOV). An FOV usually shares a common chassis including a powertrain, suspension, and wheels or tracks with a unique "box" on top consisting of associated mission-specific equipment. This type of modularity was used during World War II when the chassis from the M4 Sherman tank was used for self-propelled artillery, tank destroyers, and numerous tracked carriers (Hunnicutt, 1990, p. 281). Other examples include the M60 series of tanks and the M107, M108, M109, and M110 artillery systems in the 1950s. In general, the variants come from a production facility and are not interchangeable in theater. Probably the most ambitious examples of an entire FOV being designed simultaneously are the Armored Family of Vehicles (AFV) from the 1980s (Lopez, 1987) and the FCS from the 2000s.

Armored Family of Vehicles—1980s

The goal of the AFV was to have a common chassis and components integrated with various mission modules. A minimum number of chassis and a maximum number of common system components were planned. "Reduction in cost will be achieved through modularity, component commonality, and multiple systems capabilities combined so as to achieve required effectiveness with more survivable, cost-effective systems" (Sunell et al, 1987, p. VI–7). Army studies had indicated that using a common chassis and common components could reduce future operational and support (O&S) costs.

Originally, 29 different mission modules were to be built on four weight-class platforms (Armored Vehicle Technologies Associated [AVTA], 1988, p. 578). Due to the high costs involved in developing so many systems, the number of variants kept dropping until the program was eventually scaled back to four vehicles on a heavy chassis and two on a medium chassis (ASM [Armored System Modernization] Program, 2013). The four variants on the heavy chassis included the Block III tank, the Future Infantry Fighting Vehicle, the Advanced Field Artillery System, and the Combat Mobility Vehicle (Figure 2). The chassis would have common elements such as engine, transmission, suspension, modular armor, and tracks. The Block III tank was given the highest priority. The downsized program was renamed the Heavy Force Modernization Program. Risk was to be minimized by designing systems for optimum commonality and modularity (Boelke, 1992).

FIGURE 2. FOUR VARIANTS TO BE BUILT ON THE ARMORED FAMILY OF VEHICLES HEAVY CHASSIS



Source: GAO, 1991

In 1991, the General Accounting Office (GAO) evaluated the program. It argued that the Army was using the Soviet threat as the justification for starting with the Block III tank, whereas the Soviet threat had diminished considerably. Due to this and the high costs of the program ($59 billion) in times of decreasing defense budgets, the GAO suggested further evaluation before proceeding (GAO, 1991). Eventually, the AFV was not implemented although versions of the field artillery system survived into the 2000s (e.g., Crusader).

Future Combat Systems—Recent Example of an Armored Family of Vehicles

The FCS program of this century (Kotchman, 2004) has many commonalities with the AFV of the 1980s. The FCS Manned Ground Vehicle (MGV) program would have replaced the Army's heavy tracked vehicles

developed in the 1960s and 1970s with lighter, more mobile combat vehicles. MGV included eight variants of tracked vehicles built on a common chassis: a mounted combat system, a reconnaissance and surveillance vehicle, a non-line-of-sight cannon, a non-line-of-sight mortar, a recovery and maintenance vehicle, an infantry carrier vehicle, a command and control vehicle, and a medical vehicle. The common chassis included the crew station, propulsion, vetronics, and suspension. They touted commonality in development, training, maintenance, tools, logistics approach, production, and computing. In all, over 70 percent of the components were designed for commonality among the variants (Zanini, 2009).

As described in a RAND report, FCS was the "largest and most ambitious planned acquisition program in the Army's history" (Pernin et al., 2012, p. xvii). However, in April 2009 then-Secretary of Defense Robert Gates cancelled most of the program. Many reasons have been given for the cancellation, which were captured in the RAND report and a subsequent Government Accountability Office (2009) report. As the vehicle weight increased from the original 19 to 30 tons due to increasing requirements, the common chassis had to be replaced with three different chassis. As with the 1980s' program, the reasons for cancellation were not directly attributable to the modular approach.

Horizontal Modularity/Common Chassis—Vehicles in Production

Despite the cancellation of the ambitious AFV and the FCS programs, many other military vehicles have evolved into families, such as the Bradley, Abrams, Stryker, and many others (Science Applications International Corporation [SAIC], 2008). In most cases, the families were not planned from the outset, but rather a unique vehicle was designed and built for a single purpose. Later the original chassis was used for variants. This had the advantage of lower initial Research, Development, Testing and Evaluation (RDT&E) costs in that only requirements for a single vehicle needed to be considered rather than trying to design a chassis to fit many roles. On the downside, the original chassis might not meet the requirements for vehicles planned later. The following discussion cites four examples of horizontal modularity.

The first example is the Stryker FOV (Figure 3), which was designed to allow fast deployment and to fill the capability gap between the heavily armored Abrams and Bradley, and the lightly armored High Mobility Multi-Purpose Wheeled Vehicle (HMMWV). The Stryker, an 8-wheeled fighting vehicle, has been produced by General Dynamics Land Systems since 2005. It comes

in several variants that share a common engine, transmission, hydraulics, wheels, tires, differential, and transfer case. Variants include an infantry carrier vehicle; a reconnaissance vehicle; a mobile gun system; a mortar carrier; a command vehicle; a fire support vehicle; an engineer squad vehicle; a medical evacuation vehicle; an anti-tank guided missile vehicle; and a nuclear, biological, and chemical reconnaissance vehicle (army-technology.com, n.d.; Stryker, 2015).

FIGURE 3. STRYKER

Source: Department of Defense

Another example, created by the Finnish Defense Industry, is the 8x8 Patria Armored Modular Vehicle (AMV) (army-technology.com, n.d., Patria; Patria AMV, 2015), which allows the incorporation of different turrets, sensors, and communication systems on the same carriage (17 to 30 tons) (Figure 4). There are three platforms: the basic platform, a high-roof platform, and a heavy-weapon platform. The basic platform can accommodate an armored personnel carrier; infantry fighting vehicle; command and control; and ambulance, reconnaissance, and other vehicle variants. The high-roof platform is suitable for command, control, and communications; large ambulance; and workshop vehicles. The heavy-weapon platform has a stronger structure for heavy-weapon systems. The AMV is used in seven countries and can carry a 14-ton payload.

FIGURE 4. PATRIA ARMORED MODULAR VEHICLE

Source: United States Navy

In a few cases, horizontal modularity changeover can be accomplished in the field, such as with the Boxer, a multirole armored fighting vehicle (Boxer, 2015). The result of a German-Dutch collaboration, the Boxer is a very large, 33-ton vehicle that has a number of mission modules that can be interchanged in the field to accomplish different goals (Figure 5). Mission modules can be interchanged in an hour to create an armored personnel carrier, an infantry fighting vehicle, or an ambulance among others.

FIGURE 5. BOXER MULTIROLE ARMORED FIGHTING VEHICLE

Source: Boxer, 2015

Another recent example of a modular vehicle that can be interchanged in the field is the Cameleon IV440 Modular Mission System (Figure 6) developed by OVIK in the United Kingdom (OVIK Cameleon, 2015; OVIK Crossway, n.d.). It was originally designed in 2010 for a 4x4 chassis with modules for defense or commercial applications. Since then, it has expanded to heavier systems and is now available on platforms ranging from 5.5 to 40 tons. Seven modules are available, including patrol vehicles, weapons platforms, fuel bowsers, and power generators, with many more in development. The base platform includes a hydraulic system to enable rapid platform reconfiguration. Module changeover can be accomplished by one man in only 1 minute. The modules are expected to last three times longer than the base vehicles.

FIGURE 6. CAMELEON DE-MOUNTABLE FUEL BOWSER WITH AMBULANCE AND PATROL MODULE IN REAR

Source: OVIK Cameleon, 2014

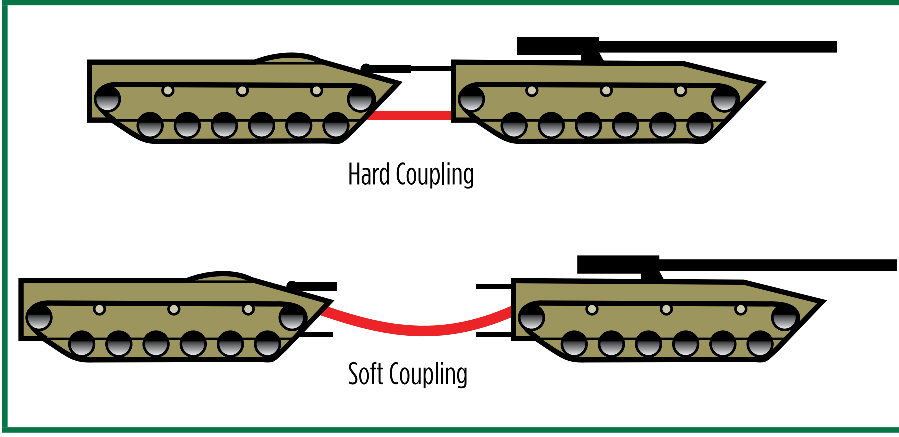
Vertical Modularity

In this modular construct (see Figure 1), two units are joined together, either directly or articulated. The two units would typically have different purposes, and each could carry some combination of crew, power unit, and mission equipment. The separate units could be independent or dependent.

As part of the AFV program, a side study was conducted on coupled vehicles (Figure 7), in which a pair of armored vehicles was considered as a substitute for the M1 tank (Schwartz, 1988). A large part of the motivation was to lower the weight of individual units compared to the M1 tank; each unit would be

less than 40 tons. Further modularity could be added by having two different weight units; for instance, a 20-ton unit and a 30-ton unit could be used singly or in pairs to produce 20-, 30-, 40-, 50-, or 60-ton vehicles.

FIGURE 7. COUPLED TANKS WITH HARD AND SOFT COUPLING



Source: Schwartz, 1988

In the original nomenclature, the two units could be hard-coupled or soft-coupled with a communication link allowing greater separation between units. Both units would be independently powered. The front vehicle would carry the main gun and ammunition. The second vehicle would carry the crew, a secondary armament, fire control, and control and communications equipment. Schwartz (1988) saw survivability advantages in several areas: the rear crew vehicle would be protected by the front vehicle from enemy fire or mines; the crew would be separated from the munitions; if the front vehicle were disabled, the rear vehicle could separate and return to base; and finally, the crew vehicle could operate at a safe standoff distance in the case of soft coupling. Although the total footprint of a coupled tank would be greater, each part would be smaller, narrower, and less weighty than an M1, allowing for easier transport. The lower weight would also translate into the requirement for less powerful powertrains and lighter tracks, suspension, etc. In many cases, improved mobility would result in several advantages: the lower weight would lead to lower ground pressures; the two units could push or pull each other if hard coupled; bridges and roadways with lower load limits would be accessible; and recovery vehicles could be lighter.

In the 1960s, TARDEC designed a concept vehicle with vertical modularity, the Twister (Figure 8), which was built by Lockheed Missiles and Space Corporation (Dasch & Gorsich, 2012). Each section had four wheels and its own engine. A crew of three rode in the back. It had a unique pivot yoke between the two sections, which provided pitch articulation to the front and yaw and roll between the two sections, allowing it to climb over 3-foot walls. The rear body wheels were mounted in tandem pairs on individual center-pivot, powered, sprung walking beams, which permitted a total wheel travel of 27 inches. Other innovations included low-pressure radial ply tires and power disc brakes—both cutting-edge technologies for the time. It could cover rough ground at an amazing 65 miles per hour. However, it never went beyond the prototype stage due to its complexity, cramped crew quarters, and the traditional track mentality (Wynbelt, 1972).

FIGURE 8. TWISTER

Source: U.S. Army

In the 1970s, TARDEC experimented further with vertical modularity using articulated vehicles; the goal was less toward modularity and more toward improvements in off-road mobility. Two M113s were connected through a cybernetically controlled articulation joint invented by TARDEC, which featured positive pitch and yaw control with roll freedom that provided force feedback to the operator (Figure 9). Two hydraulic cylinders mounted on the

vehicles provided the force to control the relative pitch and yaw between the two coupled M113s. A single M113 could climb an 18-inch high obstacle, but the two articulated M113s could climb a 5-foot wall. The articulated vehicle could also cross open trenches up to 10 feet wide; climb a 60 percent slope; enter, cross, and exit a waterway; and be controlled from either the front or back vehicle by means of a joystick (Beck & Kamm, 1974; 1975).

FIGURE 9. ARTICULATED M113

Source: U.S. Air Force

A TARDEC team is currently involved in a concept development and analysis project for a modular tactical truck, known as the Joint Tactical Transportation System (JTTS). The team is evaluating a medium/heavy tactical truck system that can be converted from a 6x6 to an 8x8 to a 10x10 truck in the field through the addition of extra wheels, axles, and associated hardware (Figure 10). This unique modular concept is facilitated through the use of a hybrid propulsion system and in-line motors on each wheel. When equipped with a load handling system to interchange payloads, this concept has elements of both vertical and horizontal modularity. If JTTS is realized, eight vehicle families, including 12 different chassis, can be reduced to a single system.

Figure 10. JTTS Concept Vehicle

Source: Department of Defense

Distributed Modularity

In this final form of modularity, functions are distributed among different units connected through a communications network (see Figure 1). Since some of the units are typically unmanned, there are survivability benefits for the manned control vehicles, which can operate at a standoff. The unmanned units, which require less armor, enjoy enhanced mobility due to the reduced weight.

An example of distributed modularity from the past was the Robotic Command Center (RCC) developed by TARDEC (Taylor, 1992, pp. 41–42). The goal was to allow a few personnel to control a large number of unmanned vehicles while the control center was on the move. The RCC was completed in 1992 and consisted of a control module mounted on a carrier. The module carried a commander and two driver-operators. Each operator could control two robotic vehicles (HMMWVs). This was the first successful demonstration of multiple vehicle control.

The Main Battle System (MBS) is a recent TARDEC concept that utilizes distributed modularity (Effinger & Parker, 2013; Parker & Scott, 2013). The goal is to replace a 70-ton M1A2 Abrams tank with three vehicles: a 25- to 30-ton manned vehicle with a crew of four and two 15- to 20-ton unmanned vehicles, each with a 120mm cannon. The crew of four would include a vehicle operator, a commander, and two unmanned vehicle operators. The manned crew vehicle would not need to absorb the firing load of the cannon or the weight of the ammunition. The unmanned units would not need crew-protective armor.

As shown in Figure 11, an MBS Platoon consisting of two supervision vehicles and four unmanned direct-fire vehicles could be used to replace four M1 Abrams tanks. Total crew would decrease from 16 to 8 persons. Four M1 Abrams would have a weight of ~280 tons, whereas the two MBS units would have a weight range of 110 to 140 tons—a considerable weight savings. In addition, distributing the weight over six vehicles rather than four has additional transport and mobility advantages. The supervision vehicles could be at considerable standoff from the fighting vehicles for increased survivability.

Figure 11. Main Battle System Platoon

Source: Department of Defense

Previous sections in this article described the three types of platform modularity—horizontal, vertical, and distributed—with examples of each. The most common is horizontal modularity, also known as an FOV. The next section will review various studies where the authors quantitatively estimated the benefits and burdens of modularity.

Benefits and Burdens

Various attempts have been made to quantify the costs and benefits of the use of modular systems. In this section, the authors review seven studies, of which four are from the era of the AFV. Due to the envisioned

size of the AFV program, considerable effort went into evaluating costs. The final three studies are from analyses of more modern modular vehicles and concepts.

The costs/benefits of the AFV were evaluated by the Advanced Vehicle Testing Activity (AVTA) made up of Food Machinery Corporation, General Dynamics, and smaller companies. They conducted a Life Cycle Cost Analysis of the AFV (AVTA, 1988). The AVTA concluded that "the total costs shown for the Development, Production, Fielding, and Sustainment of the AFV Family of Vehicles (Heavy, Medium, and Light, Wheeled, and Trailer groups) provide a very adequate baseline for the quantification of Life Cycle Cost savings" (AVTA, 1988, p. 578). Most of the savings came from common functional packages leading to savings in development, procurement, training, and support costs. Average savings from the packages were in the 15–30 percent range, distributed across the entire life cycle. These are very significant savings since the O&S costs typically dwarf the research and design costs.

A second 1988 study on battle damage assessment and repair found that damaged vehicles could be repaired and returned to battle more quickly in the case of commonality (Kane, 1988). A final 1988 study found a negative impact from a modular AFV fleet; it compared the costs of combat service support, supply, maintenance, and transportation between an AFV fleet in theater and a conventional armored fleet upgraded to an expected 2005 configuration (Cunningham, Tollefson, & Malcolm, 1988). They found that the AFV fleet would be more expensive in theater, primarily because the overall fleet weight would be greater. When using a single chassis for all heavy vehicles, the chassis has to be big enough and powerful enough to support the heaviest vehicle in the class. They found the weight of all heavy tracked vehicles was 50 percent greater in the AFV case, which led to higher fuel usage and more maintenance personnel, as required, for heavier tracked vehicles.

In the study of coupled vehicles discussed earlier, a cost model known as TREAD was used to estimate production costs of a fleet of coupled tanks relative to a fleet of M1 tanks (Schwartz, 1988). Certain costs would be higher such as armor due to more surface area, and sensors and communication equipment between the two units. Other costs would be lower due to the common chassis and the fact that fewer reserve units would be required. The final estimate was that in a coupled fleet with less armor on the front, an unmanned unit would cost 2–5 percent more than a tank fleet unit. If

both units were produced with armor comparable to the M1, costs would be 14–19 percent higher for the coupled vehicles. Other costs such as research and development (R&D) and O&S were not considered.

During FCS Phase I, SAIC evaluated the conventional unique vehicle concept versus a modular concept for an 18-ton platform (SAIC, 2000). Using TARDEC's taxonomy, they determined that horizontal modularity was more efficient than vertical modularity due to poor mobility and survivability characteristics of independent modules and the need for a complex and heavy mating joint. However, the horizontally modular platform was also not ideal because it required a heavier hull structure to implement; the structure would have to be heavy enough to accommodate the largest, heaviest variant, meaning that the powertrain, suspension, tracks, etc., would be overdesigned for lighter variants. In addition, the modules would require a ballistic joint that would be difficult to seal. Overall, they calculated that unique hulls are 10–30 percent more weight/volume efficient than a horizontally modular platform.

Readers are referred to an SAIC (2008) report that did a comprehensive investigation of acquisition costs for an FOV concept, including estimated acquisition costs. They compiled a comprehensive table of the existing "Families of Vehicles" that includes the Bradley, Abrams, Light Armored Vehicle, Stryker, M113, HMMWV, Family of Medium Tactical Vehicles, and Heavy Expanded Mobility Tactical Truck. They initially assumed that the development phase for an FOV would be burdensome due to the need to meet requirements for several variants. However, they learned that in most cases, a single unique vehicle is designed and built. Later, other variants that make use of the original chassis are added. Cost savings follow:

- An RDT&E effort needed to develop new variants is minimized.
- Shared learning-rate effect, economies of scale, and the cost-benefit of reduced training times lower production costs.
- O&S costs are reduced through quantity discounts and greater economies of scale in purchasing parts.
- A high level of commonality decreases the training needed for maintenance.

SAIC estimated that a base vehicle for an FOV would cost 50–100 percent more than a unique vehicle in RDT&E costs. However, each additional variant would only require 7.6 percent of the unique vehicle costs. Based on the SAIC analysis, as more variants are added the more cost-effective the FOV concept becomes.

On the other hand, SAIC mentioned that the later vehicle plans sometimes had to be abandoned because the original chassis could not meet the expanded requirements. Its example was from 1990, when the M1 Abrams chassis was to be developed into a tow vehicle to replace the M88 recovery vehicle and an early version of the Breacher Vehicle. Neither was successful because the Abrams power pack wasn't well suited to these applications. Another example of an unsuccessful attempt at modularity was the self- propelled howitzer, SP70, developed by the United Kingdom, West Germany, and Italy in the 1970s. It made use of a modified Leopard tank chassis (Craven, 1983). The collaborative effort was unsuccessful because the chassis design forced a complicated ammunition handling system that frequently failed.

TARDEC's Advanced Concepts Team considered the weight and space penalty from a vertical modularity concept vehicle, known as the RAVE (Iler, 2009). For two 10-ton units, they estimated that the coupling unit, the batteries, and the robotic components would add 39 ft^3 and 3,940 lbs. over a

unique vehicle—an increase of about 10 percent in weight. In addition, two structural walls were needed at the connection point, whereas one or none are needed in a unique vehicle.

Table 1 summarizes the studies described in this section. Some studies were evaluating only one facet of modularity such as repair costs. Overall, three studies found a net benefit, three found a net burden, and one found it could go either way depending on the assumptions. So many variables are affected by modularity during the different phases of design, engineering, production, usage, repair, and sustainment that a definitive answer will depend on circumstances.

TABLE 1. VARIOUS MODULARITY STUDIES AND DECISION AS TO BENEFIT OR BURDEN

Vehicle Group	Reference	Benefit or Burden	Comments
AFV	AVTA	Benefit	15–30% savings in development, procurement, support
AFV repair	Kane	Benefit	Due to commonality
AFV Cost in Theater	Cunningham, Tollefson, & Malcolm	Burden	Higher fleet weight due to common chassis
Coupled Vehicles	Schwartz	Benefit or Burden	Depends on whether front vehicle is fully armored
FCS Phase I	SAIC	Burden	Overdesign; parasitic hull weight
Families of Vehicles	SAIC	Benefit	Reduced costs in design, commonality, economies of scale
RAVE weight analysis	TARDEC	Burden	10% increase in weight

Summary and Discussion

Based on the taxonomy developed by TARDEC's Advanced Concepts Team, three types of modularity were considered: horizontal, vertical, and distributed. By far, the most common today is horizontal, also described as an FOV, in which a common chassis and powertrain are used for a number of variants. An important aspect of structural modularity is the ease of changing from one vehicle variant to another. Can it be done in the field,

or at a depot, or only in a production facility? In the vast majority of cases, these variants are purchased as is from the manufacturer and are not interchangeable in the field. A summary of the advantages and disadvantages of each type of modularity is captured in Table 2.

TABLE 2. ADVANTAGES AND DISADVANTAGES OF VARIOUS FORMS OF MODULARITY

Type of Modularity	Advantages	Disadvantages
Horizontal Modularity	• Reduced design for later vehicles • Commonality is built in	• Designing entire family from scratch may be impossible • Variants usually from production facility • Must be overdesigned to accommodate largest variant
Vertical Modularity	• Decreased weight of each module • More transportable • Reconfigurable in field • Unmanned modules need less protection • Articulated has greater mobility	• Overall weight greater • Some parts must be duplicated in each module
Distributed Modularity	• Decreased weight of each module • More transportable • Reconfigurable in field • Most flexible of all systems • Unmanned modules need less protection	• Overall weight greater • Greatest need for semi-autonomous modules • Some parts must be duplicated in each module • Need good communications networks • Greatest complexity

From the previous discussion, there are obviously some advantages and disadvantages to modular vehicles. Held et al. (2008, p. 3) determined that "nuanced decision making is required" to gain a significant benefit from commonality. The same can be said of modularity. Some points to consider are captured in the following discussion:

Design Considerations

- For any modular vehicle, design and RDT&E considerations will be more extensive than for a unique vehicle.

- If the chassis for a unique vehicle is used later for additional vehicles, design and R&D requirements will be less for succeeding variants. Conversely, the original chassis might not support requirements of succeeding variants.

- Attempts to design an entire FOV can easily become overwhelmed by competing requirements for the variants.

Weight

- In many forms of modularity, the total weight of the modular vehicle will be greater than that of a unique vehicle, due to overdesign for some variants, parasitic structure, and possible extra sensors, powertrains, communication devices, etc., if the modules are capable of independent mobility.

- In the case of vertical or distributed modularity, the individual modules each weigh less than the total vehicle, which has benefits for transport and mobility.

- In the FOV example, the chassis will need to be heavy and powerful enough to support all variants. This overdesign requirement would increase vehicle size/weight for some variants.

Adaptability

- Since the vast majority of today's horizontally modular/common chassis vehicles are factory-produced, no gain in operational adaptability occurs.
- Vehicle variants that can be interchanged in the field are exceptional today. However, two recent examples were provided: the German-Dutch Boxer and the United Kingdom Cameleon, which can be rapidly changed from one variant to another.

Costs/Benefits

- The use of the modular approach in vehicles is a potential solution to address combat developer and program requirements for supportability, cost, and adaptable and flexible vehicles.
- The modular approach comes at a price in trade-offs, which must be considered when applying it to a vehicle development effort.

Path Forward

Modularity undoubtedly has strong potential benefits in lowered costs and a more adaptable force. However, the survey of successful and failed modularity attempts does not present a clear picture to assess the benefits of modularity. As quoted in a recent study, "the effect of modularity on the entire fleet must be considered with a careful analysis of both performance and life-cycle cost implications" (Bayrak et al., 2015, p. 2). Two studies have recently been initiated to delve deeper into these issues.

TARDEC has initiated a study through the ARC to establish a modeling framework for assessing the adaptability and costs of a modular military vehicle fleet (Bayrak et al, 2015). Their efforts center on model simulations of powertrain demands, fleet operations, transportation costs, operating costs, and acquisition costs, with a comparison of a modular fleet versus a conventional fleet. Unlike earlier examples, the design of the individual modular vehicle is not being considered. Rather, its modeling framework includes the following items:

- Function Selection and Attributes
- Conventional and Modular Fleet Models
- Mobility and Fuel: Powertrain Models
- Fleet Operation Models
- Cost Models
    - Transportation
    - Acquisition Considering Manufacturing
    - Fleet Operation

Building on the ARC effort, the ONR announced a Vehicle Agnostic Modularity Project Plan (VAM, 2014, p. 28), with a goal of understanding and demonstrating modular vehicles. The hypothesis of VAM is that a well-structured application of modularity will “extend tactical range, extend operational reach and increase endurance in the field, reduce excess capacity and reduce logistic footprint/burden, enhance small unit effectiveness, lighten the Marine Air-Ground Task Force load, enhance commonality, and reduce Total Owner Cost” (VAM, 2014, p. 41). Over the course of several years, VAM will explore the benefits of vehicle modularity as well as its challenges.

An underlying premise of these studies is that a unique vehicle geared to a specific mission will always outperform a modular vehicle. However, over a set of varied missions over a longer timeframe, the modular fleet may offer cost and agility benefits compared to a conventional fleet. These efforts by ONR and TARDEC are providing decision makers a framework to determine the value of modular fleets in operational environments.

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Technology Approach: DOD VERSUS BOEING (A Comparative Study)

A. Lee Battershell

This is an analysis of different approaches in the use of technology by Boeing and DoD to determine how they may have affected development time for the C-17 and the Boeing 777. Boeing's focus on cost, schedule, performance, and market competition is contrasted to DoD's focus on performance. The paper concludes that the mere existence of a technology should not obscure (a) the impact its maturity may have on program cost and risk, (b) whether it will meet a real need of the user as opposed to a gold plated one, and (c) whether the added development time it may require could pose unanticipated problems for the customer, or even result in fielding obsolete weapons systems.

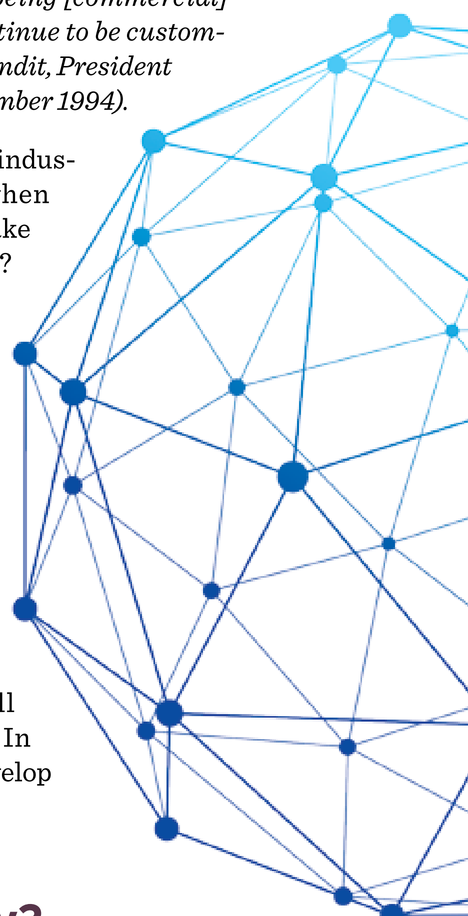
Keywords: *C-17 military cargo plane, Boeing 777 passenger plane, Air Force tactical plane, strategic airlift capability, management structure*

lead image by Diane Fleischer

> *The advantage we had in Desert Storm had three major components. We had an advantage in people, an advantage in readiness, and an advantage in technology… We need to preserve that part of the industrial base which will give us a technological advantage. (William Perry, Secretary of Defense) (Mercer & Roop, 1994)*

> *Technology must earn its way on to a Boeing [commercial] plane… In short, our R&D efforts will continue to be customer-driven, not technology-driven (P. M. Condit, President of Boeing, personal communication, November 1994).*

What are the differences in the way private industry and Government approach technology when developing planes? Why does the Government take longer than the private sector to develop a plane?



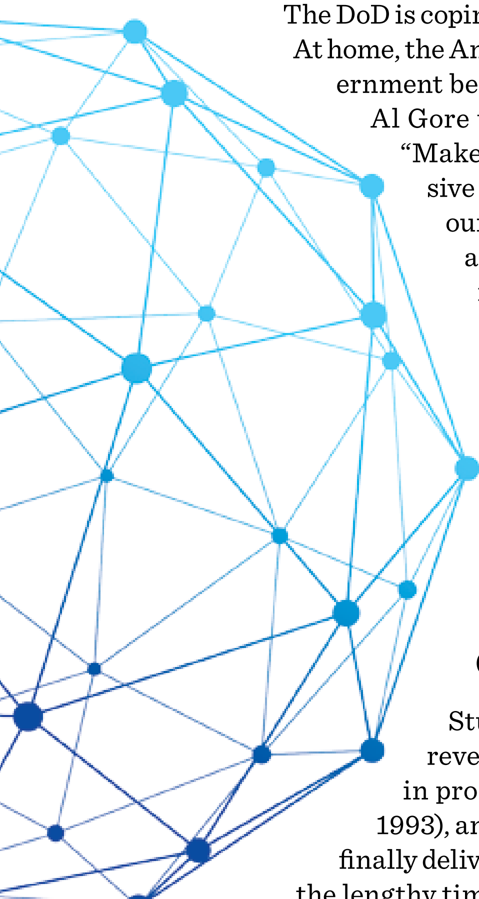
There's a perception that high technology included in military planes contributes significantly to the typical 11 to 21 years (DiMascio, 1993) it takes the Department of Defense (DoD) to develop, produce, and deploy new military aircraft. To learn if it is the technology that takes so long, this study explores the way Boeing and the DoD approached technology in developing the Boeing 777 and the military C-17. One reason for selecting the C-17 is that it does not have the complex weapons systems inherent in fighters or bombers, and yet it still took more than 14 years to develop and deliver. In contrast, it took little more than four years to develop and deliver an operational Boeing 777.

What is Technology?

According to Webster's Dictionary, technology is defined as "The applied science that includes the study of industrial arts one can apply toward practical use" (Guralnik, 1980). Technology is a method or process for handling a specific technical problem. By contrast, natural science is: "…the study of knowledge to understand the nature of the subject matter which is being studied. Its purpose is for the sake of understanding—the

application or usefulness may not be self evident at that time. Technology is the application of scientific breakthroughs" (Goldberg, 1995). When one speaks of a technology breakthrough, one is defining a new process or method for application of a scientific breakthrough.

Need for Change



The DoD is coping with reduced resources and a changing world. At home, the American public continues to demand that its government become more efficient, prompting Vice President Al Gore to initiate a National Performance Review to "Make the entire federal government both less expensive and more efficient, and to change the culture of our national bureaucracy away from complacency and entitlement toward initiative and empowerment" (Gore, 1993).

The late Secretary of Defense Les Aspin directed a "Bottom-Up Review" of DoD to identify cost savings and improve efficiency and effectiveness. In his final report Aspin said: "We must restructure our acquisition system to compensate for the decline in available resources for defense investment and to exploit technological advances in the commercial sector of our economy more effectively" (Aspin, 1993).

Studies of DoD acquisition over the past 25 years reveal that (a) DoD's way of doing business resulted in programs that spanned 11 to 21 years (DiMascio, 1993), and that (b) by the time the weapon systems were finally delivered the technology was outdated. Significantly, the lengthy time to develop weapon systems was also directly linked to a doubling of the costs originally planned (Gansler, 1989). Based on this past performance one might expect higher costs in the future. Unfortunately, the ongoing process of federal deficit reduction rules out increased military spending. DoD must learn not only to maintain the technological superiority of the American military, but learn to do so in less time and at less cost.

Assumptions

Jacques Gansler warned against DoD's continuing preoccupation with technology without consideration of cost. Substitute schedule for cost, and one could say the same is true for time. As Gansler writes:

> *Until the DoD introduces affordability [and schedule] constraints into its requirements process and shifts from a design-to-performance approach to more of a design-to-cost [and design-to-schedule] approach, it will procure fewer and fewer weapon systems each year, and eventually the United States will not have enough modern systems to present a credible defense posture. (Gansler, 1989)* [parenthetical material added to original]

It should not take 21 years to develop and deliver a weapon system nor should advanced technology cost as much as it does. Gansler points out that performance has improved in commercial as well as the defense industry because of technology, "…however, in the defense world costs have risen along with performance." Comparatively, "…commercial computers, televisions, and other items that use similar technology have improved dramatically in performance and gone down dramatically in price" (Gansler, 1989) and don't take as long to produce.

Methodology

This paper is a comparative analysis of the way Boeing and DoD used technology. The problem was to determine whether a difference in DoD's approach to technology contributed to the length of time it took to develop the C-17. This study is based on written works (published and unpublished), interviews, and observances.

Research for this report was primarily focused on the DoD C-17 and the Boeing 777. It included an extensive review of literature and interviews. The literature review encompassed studies, laws, standards, and articles relating to various approaches to technology, their focuses and parameters. The interviews were conducted with individuals who were or had been involved with the Boeing 777 or the Office of Secretary of Defense (OSD). Additional conversations with senior leaders at Boeing, the Air Force, and DoD revealed their approaches to technology use and their perceptions.

The Boeing Approach

The 777 causes me to sit bolt upright in bed periodically. It's a hell of a gamble. There's a big risk in doing things totally different. (Dean Thornton, President of Boeing Commercial Airplane Group, Main 1992)

Boeing professed a belief that one must approach technology with an eye toward utility...it must earn its way on. (Condit, 1994)

Boeing's conservative approach was illustrated in the 1970s and 1980s when it decided not to include in its 767 more advanced systems such as fly-by-wire, fly-by-light, flat panel video displays, and advanced propulsion systems (Holtby, 1986). Even though the technology existed, Boeing did not believe it was mature enough for the 767. Boeing also used what Gansler defines as a design-to-cost constraint. After Boeing defines a program it evaluates cost before going into production. Its cost evaluations include trade-offs of performance, technology, and manufacturing investments (Boeing, n.d.).

In the 1990s Boeing included in its 777 (a) fly-by-wire, (b) advanced liquid-crystal flat-panel displays, (c) the company's own patented two-way digital data bus (ARINC 629), (d) a new wing the company advertised as the most aerodynamically efficient airfoil developed for subsonic commercial aviation, (e) the largest and most powerful engines ever used on a commercial airliner, (f) nine percent composite materials in the airframe, and (g) an advanced composite empennage (Mulally, 1994). Boeing also invested in new facilities to test the 777 avionics (Proctor, 1994), and to manufacture the composite empennage (Benson, 1995). Did Boeing push the technology envelope for the 777? Philip Condit, Boeing president, said those were technology improvements, not technology breakthroughs. He used fly-by-wire technology to illustrate:

> *Fly-by-wire is interesting and you can isolate it. But if you step back, our autopilots are fly-by-wire and always have been. We've given it a little bit more authority [in the 777]. The 737 right from the start had what we called a stick steering mode in which you moved the control wheel to make inputs to the auto pilot. Fly-by-wire. The 757 Pratt Whitney engine was completely electronically controlled... it makes neat writing, but it's not an order of magnitude change. Designing the airplane with no mock-up and doing it all on computer was an order of magnitude change. (Condit, 1994)*

One only has to review the history of airplane technology during the 1980s to see that Condit is right. Airbus and McDonnell Douglas included fly-by-wire on the A340 (Nelson, 1994) and the C-17, respectively, during the 1980s, and both experienced problems. Boeing was able to learn from the mistakes of Airbus and McDonnell Douglas (Woolsey, 1994), and it had the advantage of using new high-powered ultrafast computer chips that increased throughput. In fact Honeywell, the company that McDonnell Douglas dismissed because it couldn't produce the fly-by-wire fast enough for the C-17, was the company that successfully installed it on the 777 (Woolsey, 1994)—but not without problems.

Boeing could not assemble and integrate the fly-by-wire system until it solved problems with the ARINC 693 databus, the AIMS-driven Flight Management System, and the software coding. Solving these problems took more than a year longer than Boeing anticipated. In order to maintain its schedule, Boeing did as much as it could without the complete system, then it used red-label[1] systems during flight tests. Finally, the Federal Aviation Administration (FAA) certified the last link, the primary flight computer, in March, 1995. In April, 1995 the FAA certified the 777 as safe (Acohido, 1995).

Technical Problems

While Boeing may not define its 777 avionics problems as pushing the technology envelope, Boeing did push the envelope on its design and manufacturing process, and its propulsion. As Condit said, "Designing the airplane with no mock-up and doing it all on computer was an order of magnitude change." When one is the first to use a technology in a new way, one can expect problems. Assuming that Boeing is conservative in its approach, one must ask why Boeing went from computer design to build with no mock-up, and why it used new, large, high-performance engines.

[1] A red-label system signifies that the system is still in the development and testing phase. A black-label system signifies that hardware and software are finished and ready for production.

Computer and Aircraft Design

Computer-assisted three-dimensional interactive application (CATIA) is the computer application that Boeing used to design the 777 and improve its manufacturing process (Benson, 1994). Jeremy Main best described the reasons Boeing changed its way of design and manufacture using CATIA in his article, *Betting on the 21st Century Jet.*

> *As a designer, Boeing is preeminent… I have great respect for them, but they have a long way to go in manufacturing. Therefore, to stay on top, Boeing must find ways of building planes better. If Boeing's new approach to design works, the 777 will be an efficient, economic plane with a lot fewer bugs than new planes usually have. As a result, Boeing could save the millions it usually spends fixing design problems during production and after the plane has been delivered to the airlines. (Main, 1992)*

Typically, engineers were still designing when manufacturing began, and they kept making changes as problems subsequently came to light on the factory floor, on the flight line, and even in the customer's hands after the plane was delivered.

Boeing's decision to use CATIA in conjunction with a team concept emerged primarily as a means of cutting costs after analysis revealed that the predominant cost drivers were rework on the factory floor and downstream changes. The teams that Boeing calls design/build teams include representatives from nearly every Boeing function involved in producing the transport, plus customers and suppliers (O'Lone, 1991).

Typically, engineers were still designing when manufacturing began, and they kept making changes as problems subsequently came to light on the factory floor, on the flight line, and even in the customer's hands after the plane was delivered. For example, when Boeing delivered the 747-400 to United in 1990, it had to assign 300 engineers to get rid of bugs that it hadn't spotted earlier (Main, 1992). United was not happy with Boeing's late delivery of the 747, nor with the additional costs the airline sustained in rescheduling flights and compensating unhappy customers as a result of maintenance

delays. Boeing was deeply embarrassed by delivery delays and initial service problems of its 747 (Proctor, 1994). After a lot of research and deliberation, the company decided to use computer aided technology more extensively and change its design and manufacturing approach in order to improve its service. Yet, even though CATIA and the team approach eventually proved worthwhile, there were problems.

Boeing encountered problems in adjusting to 100 percent computer-aided aircraft design. Not only was this a technology change, it was a cultural change. Condit (1994) said engineers were reluctant to let others see their drawings before they were 100 percent complete. Ronald A. Ostrowski, Director of Engineering for the 777 Division, said one of the initial challenges was to convert people's thinking from 2-D to3-D. It took more time than we thought it would. I came from a paper world and now, I am managing a digital program (Quoted in Woolsey, 1994).

The software also had problems, and development costs ballooned slightly over budget because of CATIA. Boeing CEO Frank Shrontz said, "It was not as user friendly as we originally thought" (Woolsey, 1994).

CATIA and design/build teams were new methods for applying technology that pushed the envelope and could have impacted Boeing's delivery schedule. Instead of allowing a possible schedule slip and late delivery to its United customer, Boeing decided to apply more resources, spend the extra money, overcome its problems, and deliver its 777 on schedule. While Boeing did not state how much it spent, in April 1992 *Fortune Magazine* analysts identified $3 billion (Main, 1992) set aside for research and development (R&D) for the 777. In April 1994, an editorial in *Aviation Week and Space Technology (AW&ST)* (estimated that final R&D costs for the 777 approached $5.5 billion. Based on the analysts' evaluations one could conclude that actual R&D costs were approximately $2 billion over planned costs. But, as Alan Mulally, the Senior Vice President for Airplane Development and Definition said:

> *In our business it's very rare that you can move the end point.... When you make a commitment like we made they [United] lay out their plans for a whole fleet of airplanes so it's a big deal. They'll have plans to retire old airplanes. We could have stretched it out but it just seemed best to us to keep the end date the same and add some more resources. (Mulally, 1994)*

The wisdom of Mulally's decision was proven a thousand times over. The wing assembly tool built by Giddings & Lewis in Janesville, Wisconsin, and the world's largest C-frame riveting system built by Brotje Automation of Germany, were both run in Seattle on programs generated by the CATIA (Benson, 1995). Engineers designed parts and tools digitally on CATIA to verify assembly fit. In Kansas, Boeing's Wichita Division built the lower lob, or belly, of the 777's nose section using CATIA and digital preassembly. In Japan the skins of the airframe were built using CATIA-generated programs. Workers at all plants marveled at the way all the parts built by different people all over the world fit together with almost no need for rework (Benson, 1995). Charlie Houser, product line manager at Wichita, said it best:

> *CATIA and digital preassembly let us find areas of potential interference before we started production. The individual assemblies fit together extremely well, especially the passenger floor. That assembly includes composite floor beams, and it went together smoother than any floor grid of any size that we've ever built in Wichita. (Benson, 1995)*

Engines

Three top companies will supply engines for the Boeing 777: Pratt & Whitney, General Electric, and Rolls Royce. The aircraft was designed for two engines that are billed as:

The largest and most powerful ever built, with the girth of a 737's fuselage and a thrust, or propulsive power, of between 71,000 and 85,000 pounds compared with about 57,000 pounds of the latest 747 engine. Key factors in this performance are new, larger-diameter fans with wide-chord fan blade designs and by-pass ratios ranging from 6-to-1 to as high as 9-to-1. The typical by-pass ratio for today's wide-body jet engines is 5-to-1. Pratt & Whitney is furnishing the PW4000 series of engines, General Electric is offering the GE90 series and Rolls-Royce is offering the Trent 800 series of engines. (Donoghue, 1994)

Boeing's success at getting these three companies to produce engines never before produced represent a dramatic change from the time when the federal government was the leader in technology. For example in the 1960s General Electric didn't want to risk the cost and time to develop a high-bypass jet engine for the 747. General Electric was content to let a military development program, the C-5A, absorb the cost and time associated with enhancing high-bypass jet engine technology (Newhouse, 1982). For the 777 Boeing not only pushed for new, more powerful engines, it also pushed for early approval from the Federal Aviation Administration for the plane to fly over oceans (called ETOPS: extended-range twin-engine operations) (Mintz, 1995).

Normally, the FAA first certifies a twin-engine plane for flights of not more than one hour from an airport, then two hours, and finally, after a couple years' service, a full three hours so the plane could fly anywhere in the world. The 767, powered by Pratt & Whitney JT9D-7R4D/E turbofan engines, became the first Boeing twin to win 120-minute approval in May, 1985, but not until after it had flown for two years (Woolsey, 1991). Jerry Zanatta(1994, Director, 777 Flight Test Engineering, pointed out that engines are so reliable today, an airplane could travel on only one engine. Flying with two engines allows redundancy that a pilot wants in order to ensure safety of flight. Flying with more than two engines only increases fuel cost and operating costs unnecessarily.

Why did Boeing push propulsion technology? The answer is competition. Boeing's customer airlines are concerned about operating costs, and a two-engine plane costs much less to operate than a three- or four-engine

plane. Boeing's competition, Airbus, has a twin-engine plane (A330) (Duffy, 1994) that competes favorably with the 777. If Boeing can't deliver, the Airbus can. Still, producing a new engine was not without its problems. For example, the Pratt and Whitney engine had performed perfectly in the testing laboratory; but on its first test flight in November, 1993, it backfired several times.

The engine backfired because of differences in the rates of thermal expansion between the interior components of the engine and the compressor case. The case expanded faster than actively cooled interior engine components, creating a space between the blades and the case. After the first flight, engineers changed the software commands that direct the variable blade angle of the first four compressor stages to reduce the temperature of the air inside. On the next flight the engine worked perfectly (Kandebo, 1993).

Summary of the Boeing Experience

Boeing looked at its investment in the 777 and its manufacturing process from a tactical and strategic view. It was committed to a successful 777 that would serve its customers and protect its market share against competition for 50 years into the future. Boeing was also committed to changing and improving its manufacturing process using the power of computers so it could improve quality and cut costs well into the 21st century. As a result Boeing management and its Board of Directors were focused on what they had to do to make it all happen. They were willing to commit Boeing resources toward overcoming potential challenges that included computer and process technology.

When Boeing underestimated the challenge of the design-build concept using CATIA, it could have stretched the schedule to spread additional costs over a longer time period. But that would have meant missing the delivery date to United for the first 777. Boeing management made a conscious decision to continue and learn on its first block of 777s so that all future aircraft could benefit.

> *We could have stretched it out, but it just seemed best to us to keep the end date the same and add some more resources. (Mulally, 1994)*

The DoD Approach to Technology

> *Technology on the C-17 was not as well defined as some would have us believe. (Brig. Gen. Ron Kadish, 1994)*
>
> *I was shocked in the Fall of 1992 to discover that this airplane was being produced from paper, that they did not have a CAD/CAM system. That they had never had a CAD/CAM system. (Gen. Ronald Fogleman, 1995)*

Secretary of Defense Harold Brown justified using a fixed-price incentive contract to produce the C-17 for two reasons: (a) Congress and President Carter wanted to eliminate cost-plus contracts in order to reduce excessive overruns (Hopkins & De Keyrel, 1993), and (b) all the technology for the C-17 was already proven. The Advanced Medium STOL Transport (AMST) prototypes proved short-field take off and landing (STOL) could work, and all hardware and software was off-the-shelf (Smith, 1993a). The Air Force request for proposal stated that "Undue complexity or technical risk will be regarded as poor design" (Johnson, 1986). After McDonnell Douglas won the competition, this theme was carried over into the C-17 technical planning guide:

> *The C-17's systems are straightforward in design, are highly reliable, and represent current technology. For example, a version of the C-17's engine has been proven in commercial airline service since 1985. New technology systems, like the onboard inert gas generating system (OBIGGS), are used only where they offer significant advantages over previous methods.... Avionics and flight controls that include computer-controlled multifunction displays and head-up displays enable the aircraft to be flown and all its missions accomplished with a flight crew of only two pilots and one loadmaster. (McDonnell Douglas, 1993)*

However, the C-17 experience revealed what studies conducted during the AMST had proven and Kadish had pointed out—"the technology was not as well defined as some would lead us to believe." Although McDonnell Douglas did not develop new technologies for the C-17, the way in which the technologies were used was new. The C-17 was a new cargo airlifter dependent on a complex integrated avionics system to reduce the aircrew size to two pilots and a cargo loadmaster. By comparison the C-141 and the C-5 use two pilots, a navigator for tactical and airdrop missions (C-141 only),

two flight engineers, and two cargo loadmasters when carrying passengers (Lossi, 1995; Moen, 1995). Also, using STOL capability on a plane expected to fly 2,400 nautical miles (NM) with a 172,200-pound payload including outsized cargo was much different than using STOL on a plane expected to fly a 400-mile radius with a 27,000-pound payload. The plane would require a new wing and, as John Newhouse (1982) points out in his book, *The Sporty Game*, "There is more technology in the wing than in any other part of an airframe…production schedules are keyed to wings." The differences in design between a tactical STOL and a strategic STOL were the catalysts that caused schedule slips and cost money.

Advanced Medium STOL Transport

The AMST was the genesis for the C-17. In 1971 the Air Force contracted both Boeing and McDonnell Douglas to build a prototype that, in the words of Gen. Carlton, was "really a miniature C-5" (Kennedy, n.d.) to transport cargo in-theater. The plane was to fly a 400 NM radius mission, carry 27,000 pounds, and land on short runways using short landing and take-off (STOL) technology. McDonnell Douglas' YC-15 and Boeing's YC-14 prototypes successfully demonstrated powered lift technology in 1975 that met mission requirements (Kennedy, n.d.). In March 1976, the Air Force Chief of Staff, Gen. David C. Jones, asked Air Force Systems Command to see if it was possible to use a single model of the AMST for both strategic and tactical airlift roles, and if it was possible to develop non-STOL derivatives of the AMST prototype to meet strategic airlift missions (Jones, 1976). It appears that this strategic study originated with a note from the Chairman of the Joint Chiefs of Staff, Gen. George S. Brown, that asked "Is it practical to have an AMST with a slightly higher box pick up much of the C-5 outsized load for Europe—with air refueling as necessary?" (Lemaster, 1976).

Gordon Taylor and Gordon Quinn from the Aeronautical Systems Division at Wright Patterson Air Force Base, Ohio, were leaders in a conceptual design analysis to determine if DoD could use the AMST for strategic missions. The analysis included reviewing the ability to carry the M-60 Main Battle tank, weighing 110,000 to 117,000 pounds, on a routine basis with ranges from 2,000 NM, 3,000 NM, and 4,000 NM. Taylor and Quinn concluded that using a derivative aircraft in a routine strategic airlift role would increase AMST weight and cost significantly. To restructure the AMST from a tactical to a strategic program would require full-scale development (a larger wing, heavier structure, and different aerodynamics). Even in a non-STOL capacity the wing was the major airframe component that the study said must undergo considerable change (Taylor & Quinn, 1976). In May 1976, Brig. Gen. Philip Larsen, Deputy Chief of Staff, Systems, Air Force Systems Command, wrote:

> *It would not be cost effective to incorporate a STOL capability in a strategic airlift derivative aircraft. A strategic derivative could employ a less complex conventional flap system which would permit CTOL [conventional takeoff and landing] operations from an 8,000 foot hard surface runway under sea level standard day conditions. The aircraft would be stretched eight feet to provide a 55-foot-long cargo compartment. This would permit routinely carrying the M-60 tank and single item payloads up to 112,500 pounds, or 14 463L cargo pallets, for distances up to 3,000 NM without refueling. In this particular example, it would be necessary to increase...YC-15 wing area 69 percent and gross weight 115 percent. (Larsen, 1976)*

On December 10, 1979, Program Management Directive (PMD) No. R-Q 6131(3) formally cancelled the AMST program. On that same day PMD No. R-C 0020(1) provided formal direction and guidance for activities leading to Full Scale Engineering Development of the C-X. PMD R-C 0020(1) directed that the C-X skip Milestone I and the Demonstration and Validation phase because "...the new aircraft will use existing technology... since the Air Force had demonstrated and proved advanced technology concepts and operational utility in the AMST program" (Johnson, 1986).

Changing Payload Requirements

Payload requirements changed at least five times over the life of the C-17. Beginning in 1981 the request for purchase asked for a STOL plane that could carry a payload of 130,000 pounds (Air Mobility Command [AMC],

1993). McDonnell Douglas claimed it could produce a STOL plane that could carry 172,200 pounds 2,400 miles (Johnson, 1986). When the contract was awarded in 1982, the payload requirements were changed to 172,200 pounds (AMC, 1993). DoD did not evaluate the cost to grow from a payload of 130,000 pounds to 172,200 pounds. In 1988 DoD changed the payload requirement from 172,200 pounds to 167,000 in order to accommodate the addition of a 4-pallet ramp and OBIGGS that added 5,000 pounds additional weight to the aircraft (Snider, 1992). In 1991 Gen. Hansford Johnson, MAC Commander, reduced the payload requirements from 167,000 pounds to 160,000 pounds because the kinds of equipment MAC needed to haul over essential routes—from West Coast bases to Hickam AFB, Hawaii, and from East Coast bases to Lajes airfield in the Azores—did not require a plane with a 167,000-pound capacity. He said:

> *This was not a reassessment of requirements as much as it was a refinement of the original requirements… McDonnell Douglas, in competing for the contract, offered more than what MAC needed…. All of us, being eager to do more, said sure, we'll write the specs at the higher level. (Morrocco, 1991)*

> ***Payload requirements changed at least five times over the life of the C-17.***

In January 1995, DoD, Congress, and McDonnell Douglas agreed to decrease the payload requirement even more. If the C-17 were to carry a 160,000-pound payload using STOL capability with the weight of the plane and the required fuel, it needed more powerful engines. Pratt & Whitney and Rolls Royce had produced more powerful engines, but the Under Secretary of Defense for Acquisition, John M. Deutch, said changing to more powerful engines was too costly. He preferred to reduce payload specifications rather than change engines, especially since the C-17 did not need to carry a greater payload to perform its mission (Morrocco, 1994). Fogleman said that DoD "Allowed the plane to be over spec'd unnecessarily…. We didn't need a plane to carry a 172,200-pound payload then and we don't need a plane to carry 160,000 pounds now" (Fogleman, 1995).

> *An absolute critical leg for us in this new world we are living in is how much can this airplane carry 3,200 miles... we established a 110,000-pound payload threshold at the 3,200-mile range... The original requirement set in the early 1980s was for a 130,000-pound payload, the weight of an M-1 tank then...this specification is now not considered the most critical. It was linked to the Cold War goal of transporting 10 Army divisions to Europe in 10 days, rather than how to deal with the types of regional contingencies the Pentagon now is focusing on in its planning. An absolute critical leg for us in this new world we are living in is how much can this airplane carry 3,200 miles.... So we established a 110,000-pound payload threshold at the 3,200-mile range which did not exist before...the aircraft meets that goal and is projected to exceed it. Sticking to the original specification would have required switching to more powerful engines. (Morrocco, 1994)*

On January 17, 1995, the Air Mobility Commander, Gen. Robert Rutherford, declared the C-17 a success when he certified it operationally capable (McDonnell Douglas, 1995). It's worth noting, however, that the program did not begin to overcome technology problems until after top-level commitment was apparent from principals like Deutch (Defense Week, 1995) and Fogleman. Fogleman essentially said this is nonsense, "We don't need that much payload capability" (Fogleman, 1995), and Deutch arranged a settlement with McDonnell Douglas that allowed performance trade-offs and help with computer (CAD/CAM) technology. McDonnell Douglas, in turn, put their best people on the job to produce a technically proficient airplane (Morrocco, 1994). As a result of technology trade-offs and top management commitment from both DoD and the contractor, the C-17 exceeded its schedule during 1994 and met mission requirements in 1995.

Technical Problems

One might say that design problems and planning problems were at the root of technical problems that added time to development of the C-17. The underlying problem was that the players underestimated the technical challenges. Roger A. Panton, Chief of Engineering at the C-17 System Program Office at Wright Patterson AFB, said "Our primary technical problem with the C-17 was integration. We grabbed too much off the shelf and tried to put it together" (Panton, 1994). Critical off-the-shelf technology included fly-by-wire, advanced materials, engines, software, and the powered lift that the McDonnell Douglas YC-15 prototype demonstrated in 1975.

The Defense Science Board added in a December 1993 report that lack of computer-aided design and engineering changes contributed to production delays (Defense Science Board, 1993). Deutch summarized some of the most glaring weaknesses (a) technical risks involved in flight test software and avionics integration; (b) structural deficiencies in the wings, flaps and slats; and (c) uncertainty of flight test program requirements (Morrocco, 1993).

Avionics Integration

> *Avionics is a term that covers the myriad of ultrarefined electronic devices on which modern airplanes rely. (Newhouse, 1982)*

On the C-17 that includes the flight control system and the mission computer. Integration of the mission computer and electronic flight control system was one of the three critical paths leading to first flight (Smith, 1990). The first test flight of the C- 17, September 15, 1991, was behind schedule (Smith, 1991) because of problems that included changing from a standard mechanical flight control system to a quadruple redundant electronic flight control system, and delays in the mission computer software and flight control software (Hopkins & De Keyrel, 1993).

In 1987, after McDonnell Douglas missed delivery of the first test aircraft, DoD reduced funding during budget reductions and moved delivery schedule for the first test aircraft three years to the right (to July, 1990) (Mastin, 1994). In addition, in January 1988, Congress deducted $20 million from the C-17 during its budget review, but invited DoD to ask for reprogramming of funds (SAF/AQ, 1989). DoD declined.

Flight Control System

McDonnell Douglas changed to an electronic flight-control system to prevent the plane from entering into a deep stall (Hopkins & De Keyrel, 1993). Wind tunnel testing revealed that the C-17 design caused deep stall characteristics. In 1987 the Sperry Corporation (the flight-control subcontractor) told McDonnell Douglas that the mechanical flight control system could not prevent pilots from putting the airplane into an irreversible stall (ASD/AF/C-17, 1987). After confirming that the aircraft configuration and the mechanical flight control system could allow the aircraft to enter an uncontrollable stall during certain tactical maneuvers, Douglas directed Sperry to change the mechanical flight control to a fly-by-wire system (Smith, 1993). During this same period Honeywell, Incorporated, purchased the Sperry Corporation.

In June 1989, Honeywell officials established, April 25, 1991, as the new delivery date for flight qualified software. The additional delay added four years from the time Douglas first asked for the system change until delivery (1987–1991). Even though Honeywell successfully completed an interface control document (ICD) in July 1989, showing how the electronic flight control system (EFCS) interacted with subsystems, the additional delay was too much. Brig. Gen. Michael Butchko, Air Force C-17 program manager, convinced Douglas Aircraft to hire General Electric (GE) for development of a similar system as a precautionary measure (Hopkins & De Keyrel, 1993). Douglas ended Honeywell's contract for the EFCS in July 1989 (Thomas et al., 1990). GE delivered the version 1 software for integration testing in October 1990 (Thompson, 1991).

Mission Control Computer

The three mission computers receive data from other systems, analyze data, perform calculations, and display information to the pilot and copilot. The computers act as the heart of the automated avionics system and perform functions normally done by the flight engineer such as determining an estimate of position and velocity, weight limits, airdrop, small airfield approaches, and system management (Thomas et al., 1990). Each

mission computer performs its calculations and then compares its results with the solutions broadcast over the data bus by the other two computers (McDonnell Douglas, 1993).

Douglas awarded a firm-fixed-price contract to Delco in July, 1986, to develop the mission computer (Mundell, 1990). In August 1988, an independent review team that included personnel from McDonnell Douglas, Hughes Electronics, and the Air Force concluded that Delco had not adequately accomplished system engineering and that McDonnell Douglas had not adequately defined the mission computer system requirements. Delco developed the mission computer software enough to hold a critical design review of the detail design in April, 1989 for the first of two increments of software, but it would not commit to a plan for completing the mission computer. In July 1989, Douglas and Delco signed an agreement that partially terminated Delco's contract for the mission computer subsystem, and Douglas assumed responsibility for managing the overall software development effort (Thomas et al., 1990).

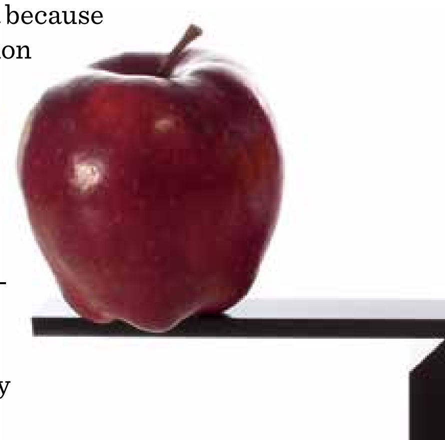
McDonnell Douglas subcontracted a majority of software for the C-17 to subcontractors and suppliers. During this process Douglas did not specify a specific computer language, which resulted in software for the C-17 in almost every known language of the time (AW&ST, 1992). Integration of the software was a nightmare that the Government Accounting Office (GAO) said resulted in "The most computerized, software-intensive aircraft ever built, relying on 19 different embedded computers incorporating more than 80 microprocessors and about 1.3 million lines of code" (Hopkins & De Keyrel, 1993). The final software release was in September, 1994, with upgrades through March 1995. David J. Lynch, in his article "Airlift's Year

of Decision," said that in 1994 the mission computer remained slow and did not meet the desired throughput capacity requirements (Lynch, 1994). John Wilson, C-17 deputy program manager, acknowledged that the program office needs to consider software improvements:

> *This is a tough area. The C-17 System Program Office recognizes that additional throughput could be beneficial. Although the computer performs the basic mission, it is slow and does not meet the desired throughput capacity. We are working the area. (Wilson, 1995)*

Wings

The wings, flaps, and slats combine with high thrust engines and the electronic flight control system for STOL. Exhaust from the jet engines force air over wings and flaps, generating additional lift. Engines on the C-17 are mounted under the wings and large flaps protrude down into the exhaust stream. The engine exhaust is forced through the flap and down both sides of the flap, creating significant added lift. The externally blown flap system and the full-span leading edge slats enable the C-17 to operate at low approach speeds for short-field landings and for airdrops (Henderson, 1990). Powered lift enables the C-17 to land on shorter runways than current, large-capacity transports by allowing it to fly slow, steep approaches to highly accurate touchdown points (McDonnell Douglas, 1993). In October 1992, the wing failed a wing-strength test (Morrocco, 1993). Even though Air Force had reduced the maximum payload requirements in December, 1989 from 167,000 pounds to 160,000 pounds at 2,400 NM, the wings were still not strong enough to handle a full payload (GAO, 1994) along with the fuel and structure weight at a 1.5 safety factor. Causes of the failure included a computational error in the initial design, optimistic design assumptions, and the method used to determine compression stress (Huston et al., 1993). The wing modifications covered a large area because McDonnell Douglas used the erroneous computation throughout the wing structure (Smith, 1993).



The failed strength test was preceded by persistent fuel leaks around the wing in September 1991, because holes were not drilled and fastened properly. Douglas held up delivery of Production Aircraft for nearly a month while technicians located the leaks. Jim Berry, then Douglas vice-president and general manager of the C-17 program, said the problems stemmed primarily

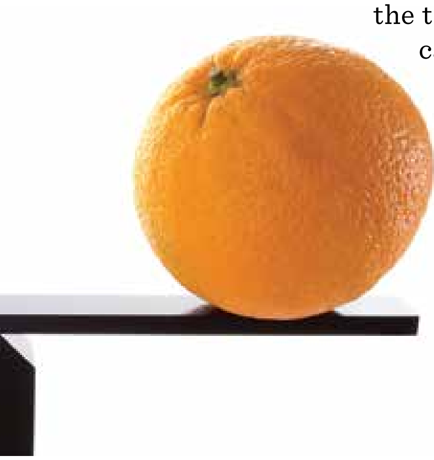
from a lack of production discipline and unscheduled work. The failed wing-strength test and persistent fuel leaks around the wing cost McDonnell Douglas more than $1 billion, and modifications added an additional 700 pounds in aircraft weight (Smith, 1993).

Summary of the DoD Experience

DoD did not look at its investment in the C-17 from a technically strategic view, nor did it appreciate the challenge of C-17 STOL technology. When DoD changed the mission of the tactical STOL to a strategic STOL, both McDonnell Douglas and the DoD underestimated the scope and cost of the effort necessary to reduce the aircrew size to three persons and fly 2,400 NM with a 172,200-pound payload. As Fogleman said, DoD "...allowed the plane to be over spec'd unnecessarily.... We didn't need a plane to carry a 172,200-pound payload then and we don't need a plane to carry 160,000 pounds now" (Fogleman, 1995). In both cases (reducing aircrew size and requiring STOL) McDonnell Douglas had to increase its use of computerized flight controls in order to maximize performance. In all cases lack of experience with software caused schedule delays and increased cost. In addition a math error caused problems that prevented the C-17 wing from passing the stress test at 150 percent. If McDonnell Douglas had a CAD/CAM system like CATIA, it might have detected and prevented both the stress problems and the fuel leak problems.

Contrasting the DoD and Boeing Approaches

Boeing's focus during the design and acquisition process was on cost, schedule, performance, and market competition. DoD's focus during the design and acquisition process was on performance. Boeing looked at the technology included in its airplane more realistically and did not try to include more than the market would buy. DoD, on the other hand, gold-plated requirements by providing more capacity than the customer needed, and underestimated the STOL technology and cost needed to carry a 172,200-pound payload. Boeing used the CATIA computer program to help revolutionize its design and manufacturing plant so that parts would fit right, and built an entirely new plant to integrate and test its new avionics package. Boeing's investment in



infrastructure helped overcome its many computer and avionics problems. DoD's contractor, McDonnell Douglas, designed the C-17 on paper. McDonnell Douglas did not use a computer program that could have identified and helped eliminate both the wing stress and the fuel leak problems, and it did not adequately plan integration of the C-17 avionics package.

When Boeing underestimated the time and cost to overcome technical problems in the 777 fly-by-wire and CATIA, it determined what it needed to do to correct the problems. Boeing decided to meet its delivery date to United, and commit additional money and resources to solve the technical problems. DoD, on the other hand, upon learning that McDonnell Douglas could not meet its first scheduled flight because of technical problems that included software and STOL design, took money away from the program and stretched it out three years.

What happens is that DoD takes so long to overcome technology problems that by the time a weapon is complete, the technology is outdated.

Jacques Gansler in his book, *Affording Defense,* explains how DoD's preoccupation with technology is self defeating:

> *The unreasonably long acquisition cycle (10-15 years)...leads to unnecessary development costs, to increased "gold plating," and to the fielding of obsolete technology. (Gansler, 1989)*

What happens is that DoD takes so long to overcome technology problems that by the time a weapon is complete, the technology is outdated. In the case of the C-17, that's true. It is the most versatile up-to-date cargo plane the United States currently has, but DoD couldn't produce the C-17 until the technology problems of design, fly-by-wire, embedded computer systems, and wing stress were solved. As a result, Boeing completed the 777 at about the same time even though it was conceived several years after the C-17. The 777 uses the same level of technology or, as with flat-panel displays, computer-design, increased propulsion, and manufacturing processes, it uses more advanced technology.

Jacques Gansler describes the dilemma between the Defense and commercial approach to technology in his illustration of a college student working in the commercial world versus one who works for defense.

> *A typical American engineering student (graduate or undergraduate) is taught how to design the "best system." Using computers, sophisticated mathematics, and all their engineering skills, these students set out to design systems that will achieve the maximum performance. If they enter the commercial world, they are taught that their designs should be modified to reduce the likely costs of production and operation. However, if they enter the defense world, they continue to use the design practices they learned in school, and cost-cutting becomes an exercise for the manufacturer. (Gansler, 1989)*

If DoD continues its past preoccupation with technology, it will fall behind. In the past, commercial development programs leveraged the technology developed by the military; this was certainly true for the 777 fly-by-wire. However, the military is now learning from commercial developers. The F-22 and other acquisition programs are using the integrated product teams that Boeing developed in its design-build approach. The F-22, the B-2, and the V-22 Osprey are all benefitting from CATIA and the strides Boeing made in composite manufacturing. However, the programs are not benefitting from Boeing's design-to-cost approach.

Conclusions

Did the difference in approaches to technology contribute to the length of time it took to develop the DoD C-17 compared to the Boeing 777? One would have to say yes. The most telling difference was how Boeing and DoD reacted to technical problems that threatened to impact delivery dates. Boeing added more resources to overcome technical problems whereas DoD took resources away and moved the delivery date out three years. As long as DoD overestimates the maturity of technology it wants to use, asks for more technology than it needs, does not commit resources to overcome technology problems in a timely manner, and does not require cost, schedule, and technology trade-offs during evolution of the design, it will take longer to develop weapon systems.

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TAPPING Transaction Costs to Forecast Acquisition COST BREACHES

Laura E. Armey and Diana I. Angelis

This article uses transaction costs to predict the probability of incurring a cost breach in a major defense acquisition program (MDAP). As transaction costs are not explicitly measured for MDAPs, the authors use estimates of systems engineering and program management (SE/PM) costs as a share of overall program costs as a proxy for transaction costs. Using survival analysis, a new approach to predicting cost breaches, they also found that an increased share of SE/PM costs in initial program estimates can help predict future cost breaches.

KEYWORDS: systems engineering, program management, survival analysis

lead image by Diane Fleischer

Controlling cost growth for a major defense acquisition program (MDAP) has been problematic in the Department of Defense (DoD) for many years. A 2007 RAND study of cost growth in DoD weapon systems determined that the cost of the 46 programs studied was more than 1.46 times the cost estimate for Milestone B (program initiation) (Younossi et al., 2007). According to the Government Accountability Office, active MDAPs in Fiscal Year (FY) 2011 collectively experienced a cost growth of $74.4 billion (Sullivan, 2011).

The Selected Acquisition Report (SAR) was introduced in 1967 to provide DoD and the Congress a summary of each MDAP's ability to meet cost, performance, and schedule objectives agreed upon by the program manager and defense acquisition executive. Program managers were now required to provide a brief explanation in the SAR of how and why any cost breaches occurred.

Based on evidence that this was insufficient to control cost growth, in 1982 Senator Samuel Nunn and Congressman David McCurdy introduced the Nunn-McCurdy Act (1983) to hold DoD accountable to Congress for management of program costs. The Nunn-McCurdy Act became law with the FY 1983 Department of Defense Authorization Act, establishing congressional oversight for MDAPs that exceed established cost thresholds. The Nunn-McCurdy Act has been statutorily amended a number of times over the years. One of the most significant changes to the reporting requirements occurred in the FY 2006 National Defense Authorization Act (Pub. L. 109-163), when Congress added the original baseline estimate as a threshold against which to measure cost growth (National Defense, 2006). The new standard prevents DoD from avoiding a Nunn-McCurdy breach by simply rebaselining a program.

Clearly, the ability to anticipate cost overruns before breaches occur would be extremely valuable to program managers and policy makers. However, the conventional focus on MDAP production costs potentially misses a critical clue. Angelis, Dillard, Franck, and Melese (2008) hypothesize that the higher the ratio of another key set of costs, *transaction costs* (costs associated with "source selection,… contract negotiation and management, performance measuring and monitoring, and dispute resolutions") relative to *production costs*, the greater the likelihood of schedule and cost overruns.

Higher transaction costs are typically experienced in programs that involve greater asset specificity, complexity, and imperfect and asymmetric information—in other words, programs that are at greater risk (Franck & Melese, 2008). Proxy measures first suggested by Angelis et al. (2008) that can be used to capture many of these costs include systems engineering and program management (SE/PM) costs regularly reported by MDAP contractors. It seems reasonable to assume that combined SE/PM costs will be a higher share of total overall estimated costs (production + transaction costs, as predicted at the Milestone B decision point). Program managers, therefore, could reasonably anticipate higher costs in coping with more complex and riskier MDAP projects. Unclear is whether or not these costs are explicitly considered in program cost estimates or simply reflected in the size of SE/PM staff assigned to more complex or high-risk programs.

Background

Many studies (e.g., Bolten, Leonard, Arena, Younossi, & Sollinger, 2008) have examined cost growth in DoD programs, yet little research has been done on the relationship between transaction costs and cost overruns as suggested by Angelis et al. in 2008. A 2006 RAND study established that MDAP SE/PM costs vary between programs depending on the program type (Stem, Boito, & Younossi, 2006), and Angelis et al. (2008) suggested using the SE/PM cost as a proxy for transaction costs to examine the relationship between transaction costs and cost overruns.

In general, a program has two types of costs: production costs and transaction costs. Production costs are usually captured in the Work Breakdown Structure (WBS), but transaction costs may not be adequately captured in the WBS. Because traditional cost estimates are based on the production costs found in the WBS, they do not explicitly include transaction costs

(Angelis et al., 2008). Although they are not often captured in the accounting records, the time and effort associated with complex and risky MDAP transactions represent real costs to the organization.

In previous research, Angelis et al. (2008) examined how transaction costs might be captured in the cost estimates of DoD acquisition programs. Angelis et al. identified a number of issues with DoD program management cost data reported for major weapon systems and found that they are not well suited for developing a cost model that includes transaction cost variables. As an alternate approach, they explored using contractor Program Management data from cost data summary reports (DD Form 1921) and suggested using the SE/PM category as a proxy for transaction costs. The DoD (2011a) defines systems engineering as “the technical and management efforts of directing and controlling a totally integrated engineering effort of a system or program.” Program management is defined as “the business and administrative planning, organizing, directing, coordinating, controlling, and approval actions designated to accomplish overall program objectives, which are not associated with specific hardware elements and are not included in Systems Engineering” (DoD, 2011, p. 222). The ratio of (SE + PM) costs relative to total program costs offers a potentially valuable way to compare transaction costs across different programs.

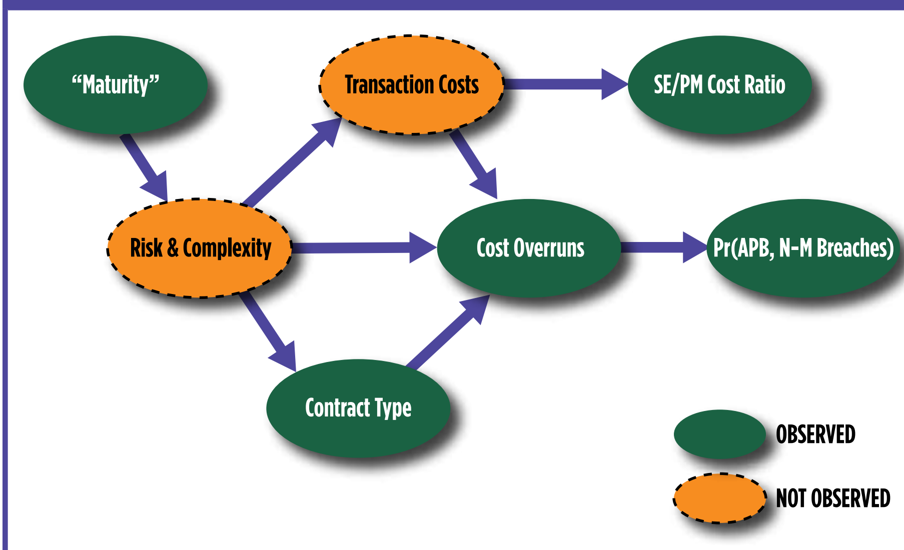
Following the method used by Biggs (2013), this study uses the SEPM cost ratio for a program as shown in Equation 1:

$$\text{SE/PM Cost Ratio} = \frac{\text{SE + PM Costs}}{\text{Total Cost}} \qquad (1)$$

The numerator of the SE/PM cost ratio is the sum of SE and PM cost expenditures and the denominator is total program expenditures (estimate at completion, or EAC). A ratio is calculated to provide a perspective on the relative magnitude of SE/PM expenditures as well as to allow for comparison across different programs. The hypothesis is that programs with higher SE/PM cost ratios are more likely to experience cost breaches than programs with lower SE/PM cost ratios. This is based on the assumption that higher SE/PM cost ratios are related to riskier contractual relationships since more time, effort, and resources are expended to meet performance and schedule deadlines when compared to less risky contracts. To the extent that this is predicted early in the program, it could be useful to policy makers by providing an early warning that programs are more likely to result in cost and/or schedule overruns.

Biggs (2013) introduced the influence diagram in Figure 1, which describes the interactions between factors that may be associated with the occurrence of a cost breach. The dashed lines in Figure 1 represent factors that must be dealt with qualitatively or by using proxies. The solid lines represent factors that can be quantitatively evaluated. While the risk and complexity of a program may directly contribute to a cost overrun, the SE/PM efforts and the contract type can influence the magnitude and frequency of cost overruns as measured by cost breaches.

FIGURE 1. COST BREACH INFLUENCE DIAGRAM



Source: Biggs, 2013

Figure 1 indicates that the risk and complexity of the MDAP will guide program managers and contractors in their selection of an appropriate contract type, which in turn can influence the government's exposure to cost overruns. In all likelihood, the risk and complexity of a program will drive the level of monitoring and negotiation (transaction costs) required to manage the program, and riskier, more complex programs will require higher levels of transaction costs. Specifically, we do not expect that transaction costs themselves drive overruns, but rather that the risk and complexity that require higher levels of transaction costs drive breaches.

Cost Breaches

In this article, we will examine how the SE/PM ratio and contract type are related to the probability of incurring a cost breach. Cost breaches occur when the amount of the cost overrun exceeds certain parameters defined by regulation. Within the defense acquisition community, programs may incur two types of cost breaches: Acquisition Program Baseline (APB) and Nunn-McCurdy breaches. For a program to incur an APB breach, estimated program expenditures must be greater than the APB EAC by at least 10 percent. If the difference is 15 percent or more, a Nunn-McCurdy breach is incurred. Cost breaches frequently are incurred in six categories of appropriations: average procurement unit cost (APUC); program acquisition unit cost (PAUC); procurement; research, development, test and evaluation (RDT&E); military construction (MILCON); and acquisition-related operations and maintenance (O&M). Each of these cost breaches was included in the data set for this study.

> ***Within the defense acquisition community, programs may incur two types of cost breaches: Acquisition Program Baseline (APB) and Nunn-McCurdy breaches.***

A formal cost estimate for a program is normally developed at Milestone B, the initiation of an acquisition program, when the APB is established. The APB is used for tracking and reporting cost and schedule for the life of the program, and it includes threshold and objective values for cost, schedule, and performance. A cost threshold breach is incurred when cost expenditures exceed the cost objective by 10 percent or more (DoD, 2013). If an MDAP has been officially rebaselined,[1] cost breaches are measured to the current baseline.

Nunn-McCurdy cost threshold breaches are based on original cost estimates for PAUC and APUC at project completion. In the case of a program that has rebaselined, cost threshold breaches are also based on the current (i.e., rebaselined) cost estimate for PAUC and APUC at project completion. For purposes of this study, a cost breach is any reported in the SAR that is greater than or equal to 10 percent above the APB. The type of cost threshold breach and the APB baseline against which it is compared are shown in Table 1.

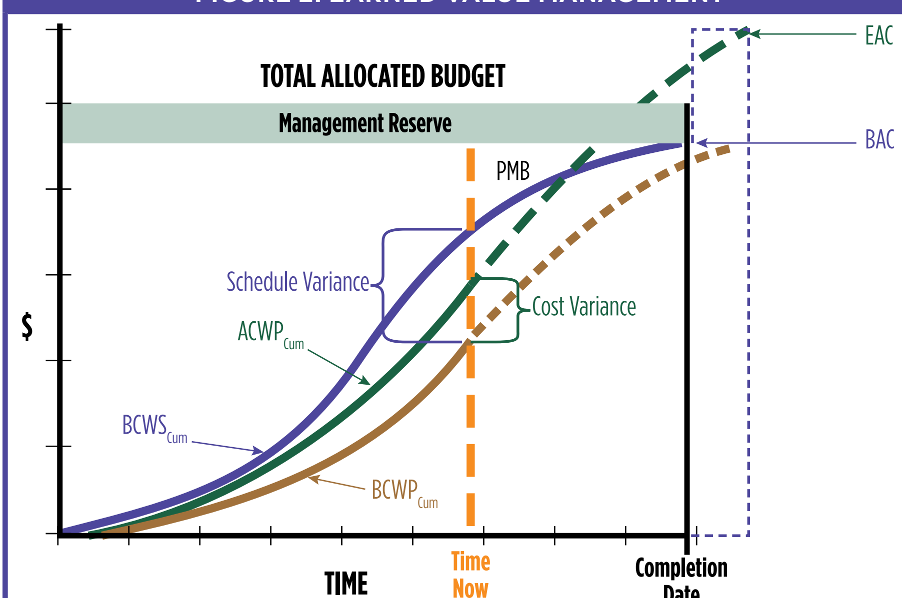
TABLE 1. APB AND NUNN-MCCURDY COST BREACH THRESHOLDS

	APB Breach (RDT&E, Procurement, MILCON, O&M)	Nunn-McCurdy "Significant" Breach (PAUC & APUC)	Nunn-McCurdy "Critical" Breach
Current Baseline Estimate	10%	+15%	+25%
Original Baseline Estimate	N/A	+30%	+50%

Source: DoD, 2013

Figure 2 can be used to illustrate cost overrun calculations. The budgeted cost of work performed (BCWP) represents the total amount budgeted for work packages that are open or completed at any given point in time. The budgeted cost of work scheduled (BCWS) represents the total amount budgeted for the work that was scheduled for completion at a given point in time. The actual cost of work performed (ACWP) is the sum of actual costs incurred to accomplish the work performed at a given point in time.

FIGURE 2. EARNED VALUE MANAGEMENT



Source: DAU Gold Card, 2015

The EAC is the sum of the ACWP and the estimate to completion (ETC) for the remaining work. The ETC can be calculated using the cost performance index (CPI) and the schedule performance index (SPI). The formula for calculating ETC is:

$$ETC = (BAC - BCWP) / (CPI * SPI) \quad (2)$$

When the EAC, a cost estimate for the total cost of the contract, is higher than the BAC, the baseline cost estimate of the contract, a cost overrun is projected. Nunn-McCurdy breaches are far rarer, perhaps because of the political threat or simply the higher threshold; thus, this article will include analysis of the potential of both types of cost overruns.

Data

This study used data originally collected by Biggs (2013) from two different data sources: SARs and the Cost and Software Data Reporting (CSDR) System. The SAR contains details of critical parameters of an MDAP, including threshold breaches, schedule, performance, current contracts, and cost details. MDAPs typically require several contracts to be executed, often concurrently. SARs provide information for the overall program and not for individual contracts. A SAR may list a single contract or many contracts for a single MDAP. Because threshold breaches are associated with contract estimates, only MDAPs that listed one contract in the "Contracts" section of the SAR were selected for purposes of this study. In addition to cost threshold breaches, the SAR indicates the time since program initiation at Milestone B, which was used in this study to indicate program maturity.

The program cost data found in the DD Form 1921 CDSR provided by the Defense Cost and Resource Center in the Defense Automated Cost Information Management System database contain significantly more contract detail than the SARs. The WBS format of the CDSR facilitates obtaining information on SE/PM costs. To simplify the data collection process, only the cost data provided by the prime contractor were recorded for further analysis. The SE/PM cost values used in this study are extracted

from the WBS line item values for "EAC SE/PM cost," which are listed on the CDSR (DD Form 1921). The EAC SE/PM cost is the projected SE/PM cost at contract completion. The SE/PM costs are inclusive of the total contract costs less the contractor's profit/loss or fees.

The SE/PM category reported by the contractor has some limitations. First, the activities included in this category will vary somewhat from contractor to contractor. As a result, a small portion of the differences in SE/PM costs between contracts may be due to differences between the accounting systems used by each contractor. The general category, however, is a reasonable measure of the cost of activities commonly associated with SE/PM. Second, the costs included in SE/PM for a single contract may vary over time as new costs are defined by the contractor as being related to SE/PM. This could explain a small portion of the increase in the SE/PM cost in some contracts, but we did not observe significant differences in our data. Finally, we recognize that the SE/PM category does not capture all possible transaction costs nor was it ever intended to. Rather, it is likely that many if not most of the activities in this category are related to transactions, as opposed to production, and thus provide a reasonable measure of transaction costs.

This article will analyze the SE/PM-to-total-cost ratios of MDAPs, looking for a potential correlation between these ratios and the probability of experiencing a cost breach. Determining the nature of any potential relationship between the SE/PM-to-cost ratio and the probability of cost breaches experienced by a program will test the hypothesis that programs with higher SE/PM cost ratios will experience cost overruns more frequently than programs with lower SE/PM cost ratios. More formally, we will test the experimental hypothesis H_1 that the probability of breach is increased by an increase in EAC SE/PM in the total cost:

$$H_1: d(\text{Probability Cost Breach}) / d(\text{EAC SEPM/Total cost}) > 0$$

$$H_0: d(\text{Probability Cost Breach}) / d(\text{EAC SEPM/Total cost}) = 0$$

The type of contract used for the program was also obtained from the CDSRs. Programs were noted as having either firm-fixed-price type contracts or cost-plus type contracts. The type of contract used for a program is an indication of the perceived level of risk associated with execution of the contract. As the level of performance risk increases, the risk of cost overruns also increases and the amount of cost risk that the contractor is willing to assume tends to decrease. Contract types differ in how the cost risk is shared between the government and the contractor. In a firm-fixed-price contract, no cost sharing exists between the government and the contractor,

and the contractor has full responsibility for the performance costs and resulting profit (or loss). In a cost-plus contract, a share ratio based on the contract cost and the contractor's fee (profit) is negotiated so that the contractor has a predetermined responsibility for the performance costs, which will directly affect the fee (profit) (U.S. General Services Administration, 2005). By including contract type in our analysis, we can account for basic risk differences recognized by both the government and the contractor at the outset of the program. Programs with aspects of both were treated as cost-plus type contracts since cost-plus contracts are a better indicator of program risk.

TABLE 2. DESCRIPTIVE STATISTICS

Variable	Obs	Mean	Std. Dev.	Min	Max
Breach—Program Av.	32	0.8125	1.090649	0	4
Nunn-McCurdy	32	0.28123	0.5226715	0	2
Program Type	32	0.516129	0.5080005	0	1
EAC SEPM from Milestone B	32	13.38844	11.58719	0.15	42.85
EAC SEPM Program Average	32	14.66727	10.68449	0.87	43.31
To Date SEPM Program Average	30	16.59583	13.81136	1.4	54.66667

Table 2 describes the data used in our study. The study covers 32 programs over 84 program years. Despite not having greatly disparate thresholds, our sample reflected far more APB breaches—26 program years—versus only 9 program years for Nunn-McCurdy breaches. Approximately half of the programs were firm-fixed-price and half were cost-plus type contracts. We also compared three different measures of the SE/PM ratio. The first measure is for the EAC of the SE/PM ratio to total costs, as estimated at Milestone B. SE/PM are on average about 13 percent of total costs estimated at Milestone B. Programs that rebaseline would update this measure, but for purposes of this study we maintain the original prebreach measure because we are interested in the predictability of breaches based on original assessments of risk. The second measure is still the EAC, but programs update this measure

as they go along. This number is about 1.5 percentage points higher than the Milestone B estimate or 14.7 percent of total costs. We also include the actual to date SE/PM to total cost at each point in time for our sample. At 16.6 percent of total costs, this is even higher than either predicted share, indicating that estimates are on average overoptimistic and that SE/PM costs grow, on average, faster than total costs.

Analysis of the data shows that more than half of the MDAPs in the study initially estimated an EAC SE/PM cost ratio of 0.10 or less and experienced fewer than two cost breaches since 1998. Furthermore, it can be inferred that most of the programs have experienced at least one cost breach, which seems to confirm a RAND report finding that most MDAPs' actual costs exceeded baseline cost estimates (Arena, Leonard, Murray, & Younossi, 2006).[2] Observations of the MDAP SE/PM-to-total-cost ratios agree with the RAND study, suggesting that trends in SE/PM costs vary across MDAPs (Stem et al., 2006). Recall that SE/PM costs are used as proxy measures of the transaction costs required to administer and manage the MDAP.

Methodology

Because our data set includes programs that have not experienced cost breaches over the time period studied, our data are considered to be "right censored." This means that ordinary linear regression is not a good option for analyzing the data. Instead, we employ survival analysis to test whether relatively high Milestone B EAC SE/PM is a predictor of cost breaches. Survival analysis is typically used in medicine and social sciences to examine when an event of interest will occur. For example, in medicine where the event of interest is a heart attack, we can use survival analysis to predict whether a patient will suffer a heart attack within a period of time. In this study, the event of interest is a cost breach, and we are interested in whether a program will experience a cost breach.

In our medical example, we could use survival analysis to identify risk factors, such as obesity, that might indicate a greater propensity for suffering a heart attack. In this study, we are looking for risk factors that might predict cost breaches. Two explanatory variables were included in the analysis: EAC SE/PM cost ratio and program contract type (fixed-price or cost-plus). While the exact nature of the relationship between cost threshold breaches and these explanatory variables is unknown, it is reasonable to presuppose that the explanatory variables influence the cost performance of the MDAPs as shown in Figure 1.

Using survival analysis, we construct a hazard function for cost breaches. A hazard function shows (over time) the probability that an event (such as a cost breach) will be incurred. As programs can experience multiple cost breaches despite rebaselining, we allow for multiple breaches over time[3] and estimate how the hazard of cost breach varies with our explanatory variables. Hazard models are also useful because they are more tolerant of gaps and censoring. Hazard models can be thought of as conditional logits (Cleves et al., 2010). We allow for repeat failures over the period—that is, following cost breaches, we allow a program to stay in the sample.

Survival analysis uses time-at-risk as its relevant time metric. Thus, we measure "survival time" in terms of the maturity of the design and technology of the system. In this study, program maturity is measured by the time elapsed since Milestone B, the entry point into the Engineering and Manufacturing Development phase. For a program to receive approval to begin Milestone B in DoD, the design and technology associated with the system must be considered "mature."[4]

In this analysis, we use the Cox-Relative Hazard. It is considered semiparametric because it does not imply a specific functional form on the hazard of breaches over time. The proportional hazard model is specified as:

$$h_j(t) = h_0(t) \exp(x_j \beta_x)$$

which states that the hazard a particular subject *j* faces at time *t* is a function of the baseline hazard modified proportionally by the vector of regression coefficients β_x. The Cox model does not estimate the baseline hazard. We can convert coefficients from these regressions to cumulative hazard ratios to understand the marginal effect on the baseline hazard of a change in the coefficient. This is done simply by calculating the exponent of the coefficient and using it as a multiplier (e.g., the value 0.9 would correspond with a 10 percent reduction, and 1.1 would be a 10 percent increase). While we report coefficients, we interpret our results using exponentiated hazard ratios—that is, the cumulative hazard of a cost breach.

We next examine whether baseline SE/PM-to-cost ratios influence the probability of a Nunn-McCurdy breach using a similar analysis. While the difference between the two is mainly the 10 percent versus 15 percent threshold, Nunn-McCurdy breaches are sufficiently rare that they may have significantly different causes.

Finally, we test the robustness of our finding using logit models. Logit is commonly used to determine the influence of exogenous variables on the probability of a dichotomous outcome, such as whether or not a cost breach occurs in any given program year. Logit is preferred over a linear regression model because, using a logistic function, it constrains all probability-of-occurrence estimates to be between 0 and 1. Formally, the logit model for the probability can be written as:

$$\mathrm{P(Breach)} = \frac{e^{x\beta}}{1 + e^{x\beta}}$$

Where $x\beta$ is a function of the vector of explanatory variables.

We are curious as to whether Milestone B SE/PM predictions are the best predictors of breaches or whether within-program changes in SE/PM estimates or actuals should cause concern about program health. To test, we use a simple logit model, which predicts the probability of failure on the baseline EAC SE/PM ratios as in our hazard model. We cluster the standard errors by program. We use a fixed effects (conditional) logit to model whether a change in either EAC or the actual SE/PM cost ratio for an MDAP will change its probability of breaching a cost threshold. Formally, this model measures the impact of deviations by the independent variable from the program's mean (Allison, 2001).

Results

We find that higher estimated SE/PM ratios are associated with a higher risk of APB breaches. Figures 3 and 4 show the cumulative risk of APB and Nunn-McCurdy breaches over program maturity. Table 3 shows the results for Hazard models for APB breaches, and Table 4 shows the results for Nunn-McCurdy breaches

FIGURE 3. HAZARD OF COST BREACH

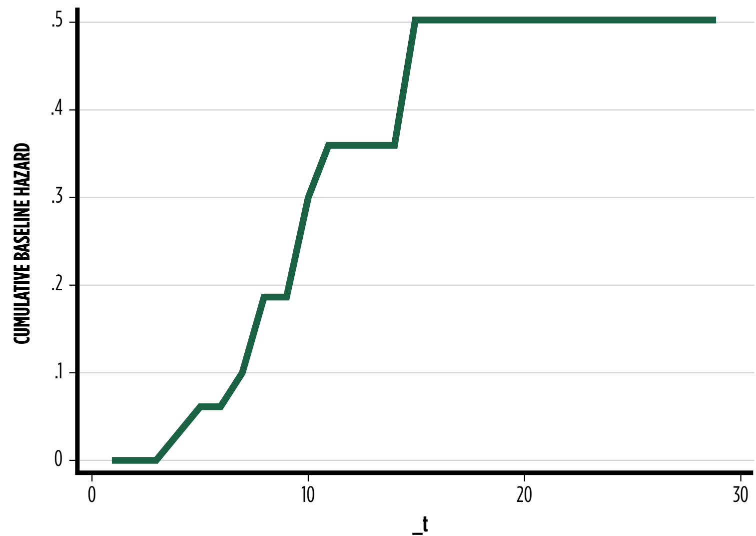


FIGURE 4. HAZARD OF NUNN-MCCURDY BREACH

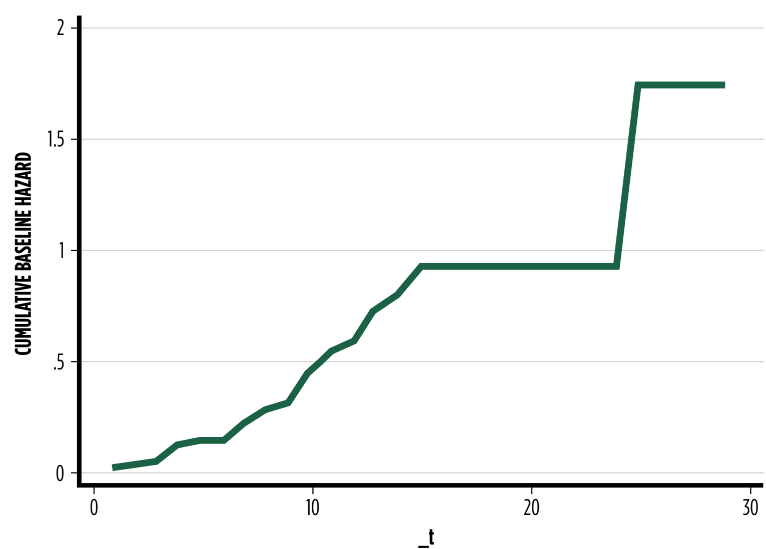


TABLE 3. APB BREACH HAZARD		
Variables	**(1)**	**(2)**
EAC SE/PM from	0.0482***	0.0284*
Milestone B	(0.0147)	(0.0168)
Type		1.125**
		(0.552)
Observations	84	84

Note. Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

In the first model a 1 percentage point increase in the estimated SE/PM ratio at completion increases the risk of breach by 5 percent, a result that is statistically significant at the 1 percent level. When contract type is added as a control, the impact of the SE/PM ratio goes down to 3 percent and its significance is reduced to the 10 percent level. Looking at the impact of contract type, we find that having a cost-plus type contract multiplies the risk of an APB breach by 3.1, which is significant at the 5 percent level.

TABLE 4. NUNN-MCCURDY BREACH HAZARD		
Variables	**(3)**	**(4)**
EAC SE/PM from	0.0247	0.00352
Milestone B	(0.0268)	(0.0290)
Type		1.269
		(0.886)
Observations	84	84

Note. Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Nunn-McCurdy breaches are significantly less common than APB breaches and SE/PM ratios or contract type do not appear to determine them. The SE/PM ratio is not a significant predictor of Nunn-McCurdy breaches, and while type has a similar magnitude to its impact on APB breaches, it is not statistically significant either.

TABLE 5. LOGIT ANALYSIS

Variables	(1) Logit	(2) Fixed Effects	(3) Fixed Effects
Baseline EAC SE/PM	0.0433* (0.0244)		
To Date SE/PM		-0.0358 (0.0491)	
EAC SE/PM			-0.0924 (0.0782)
Constant	-1.433*** (0.508)		
Observations	84	36	39
Number of programs		10	11

Table 5 shows the results of logit analysis for APB breaches. We find that the likelihood of a cost breach is related to the EAC SE/PM ratio predicted at milestone B, but not to changes in the predicted ratio or to the actual SE/PM ratio. The marginal effect of the logit model is very similar to the hazard function and statistically significant at the 10 percent level: for every 1 percent increase or decrease in the EAC SE/PM cost ratio, there is an increase or decrease of 4 percent in the probability of a program sustaining a cost threshold breach. We do not find any within-program impact using fixed effects logit models, indicating that a change in the EAC SE/PM ratio is not an indicator of a potential breach. Thus forecasts of cost breaches should focus on initial SE/PM ratio estimates.

Conclusion

This article successfully tested the hypothesis that transaction costs could help explain future cost breaches of MDAPs. Using SE/PM costs as a ratio of total program costs, we find the greater this ratio is at the outset (Milestone B estimate), the greater the risk of eventual cost breaches. This information reflects the program manager's implicit assessment of the risk of a program and can be a valuable early indicator of which programs will benefit from greater oversight. We should be careful to note that high SE/PM ratios may be the result of program managers responding proactively to program risks. As such, we are not suggesting that high SE/PM ratios are a bad thing—simply that they can be used to predict cost breaches, which often occur in high-risk, more complex programs. This suggests that the SE/PM ratio is a measurable indicator of cost risk and anticipated transaction costs.

This article also offers an innovative way of looking at cost breaches, using survival analysis to forecast cost breaches in MDAPs over a program's life cycle. We offer somewhat robust analysis, using a more traditional logit analysis, of our predictions. We believe this is a step forward in using measures available in DoD's vast databases of cost information to develop more robust forecasts of potential cost overrun risks in programs. These findings suggest that the department could benefit from capturing more explicit measures of transaction costs to determine more precisely their role in predicting cost variability.

Appendix

PROGRAMS SELECTED FOR STUDY

Active Electronically Scanned Array (AESA) Radar
AIM-9X/Short Range Air-to-Air Missile
AIM-120 Advanced Medium Range Air-to-Air Missile (AMRAAM)
Airborne and Maritime/Fixed Station Joint Tactical Radio System (AMF JTRS)
AN/WQR-3, Advanced Deployable System (ADS)
Apache Block IIIA Remanufacture (AB3A REMANUFACTURE)
AV-8B/Attack, V/STOL, Close Air Support (Harrier II+ Remanufacture)
B-2 Radar Modernization Program
Cobra Judy Replacement (Cobra Judy Replacement)
EA-18G Growler (EA-18G)
Expeditionary Fighting Vehicle (EFV)
E-3 AWACS Radar System Improvement Program (RSIP)
E-2C Reproduction
Family of Advanced Beyond Line-of-Sight Terminals (FAB-T)
Family of Medium Tactical Vehicles (FMTV)
Guided Multiple Launch Rocket System/DPICM/Unitary/Alternative Warhead (GMLRS/GMLRS AW)
Joint Common Missile (JCM)
Joint Tactical Radio System Ground Mobile Radio (formerly Cluster 1) (JTRS GMR)
Longbow Hellfire - subsystem of the AH-64 Apache Weapon System
LHA Replacement Amphibious Assault Ship
MQ-4C Unmanned Aircraft System Broad Area Maritime Surveillance (MQ-4C UAS BAMS)
Multi-Platform Radar Technology Insertion Program (MP-RTIP)
National Polar-orbiting Operational Environmental Satellite System (NPOESS)
Presidential Helicopter Replacement (VH-71) Program
P-8A Poseidon
Sense and Destroy Armor (SADARM)
Small Diameter Bomb Increment II (SDB II)
Space Based Infrared System (SBIRS) High Program
Standard Missile (SM) - 2 Block IV
Stryker Family of Vehicles (STRYKER)
UH-72A Light Utility Helicopter (LUH)
Warfighter Information Network - Tactical (WIN-T)

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Endnotes

[1] Circumstances authorizing changes to the baseline are limited; revisions to the current APB are not authorized unless there is a significant change in program parameters and must be approved by the Milestone Decision Authority (DoD, 2013).
[2] For most of the programs reviewed, actual costs exceeded the baseline cost estimate established at Milestone B (program initiation), as measured by the cost growth factor (Arena et al., 2006).
[3] For robustness, we also ran the analysis without allowing for multiple breaches, and while the results were weaker, they were still statistically significant and of a similar magnitude. Still, the fact that including multiple breaches strengthens our results, indicates that programs with high levels of complexity and risk often suffer for these high levels repeatedly.
[4] Milestone B approval authorizes an MDAP to enter the Engineering and Manufacturing Development phase of the acquisition process. Statutory requirements for MDAPs to achieve Milestone B approval are found in Title 10 U.S.C. § 2366b. These requirements stipulate that the program be certified by the Milestone Decision Authority to be affordable, fully funded through the Future Years Defense Program (FYDP), and that the cost and schedule estimates are reasonable.

Biographies

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HUMAN SYSTEMS ENGINEERING and Program Success—A Retrospective Content Analysis

Liana Algarín

This investigative study demonstrates the benefits of addressing human considerations early in the system development life cycle that will bring long-term benefit to program managers and systems engineers. The approach used a retrospective content analysis of documents from weapon systems acquisition programs, namely Major Defense Acquisition Programs. Binary logistic regression analyses were conducted to predict the effect of the presence of words relating to Human Systems Integration on the success of programs.

This investigative study corroborates the idea that some benefit may be derived from implementing Human Systems Integration during the weapon systems acquisition life cycle.

Keywords: *Human Systems Integration, weapon systems, life-cycle cost, schedule, major defense acquisition program*

Image designed by Diane Fleischer

In 1981, U.S. congressional watchdogs recommended improving weapon systems design by addressing human consideration problems early during system acquisition (U.S. General Accounting Office, 1981). Today, the process by which human considerations are included in the planning and implementation of a system is known as Human Systems Integration (HSI) (International Council on Systems Engineering [INCOSE], 2012). The benefit of including HSI in weapon systems design and acquisition is best realized by giving HSI early attention and priority during the planning stage. This article will demonstrate that a decreased percentage of HSI words in documents originated during acquisition will coincide with unforeseen costs, delays, and performance problems.

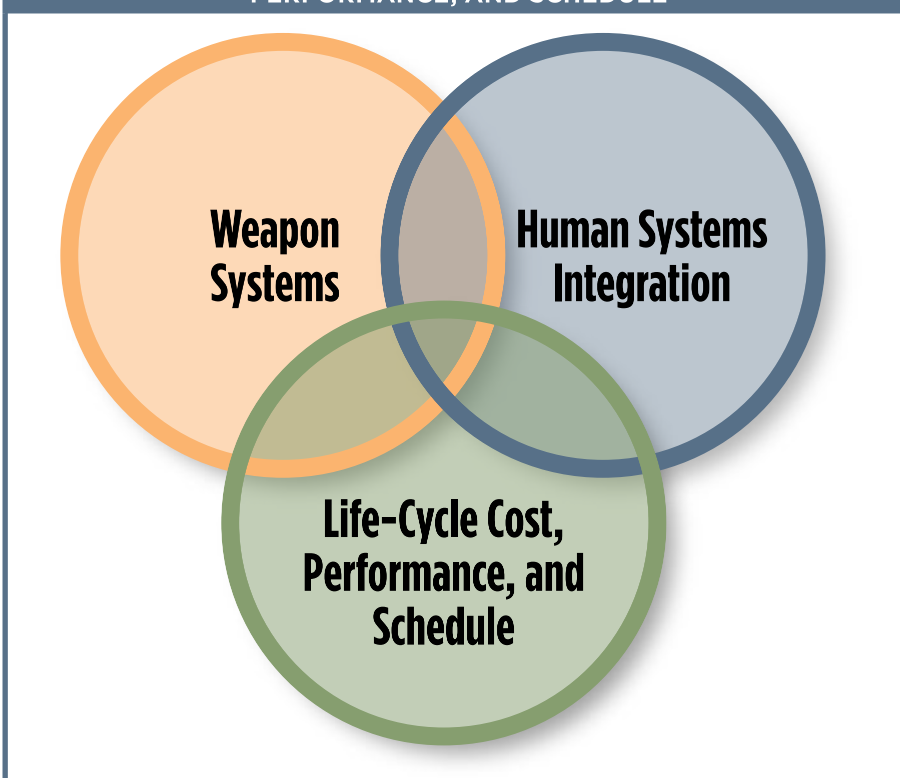
> ***The benefit of including HSI in weapon systems design and acquisition is best realized by giving HSI early attention and priority during the planning stage.***

In fact, HSI-related content in acquisition documents may influence program success. Typically, a program is considered successful if it avoids cost overruns, avoids performance breaches, or avoids schedule breaches. Systems Engineering (SE) is the interdisciplinary approach for developing systems (INCOSE, 2012). HSI is an important part of SE, and thus the acquisition life cycle (Karwowski, 2012). Understandably, the decisions that program managers and systems engineers make early in the acquisition life cycle will affect program success and life-cycle costs. For example, to help organizations with incorporating HSI into their design process, Handley and Knapp (2014) have created the Human Viewpoint tool for early implementation of HSI into the acquisition life cycle. Ahram and Karwowski (2012) warn that failing to address costs related to human performance (e.g., Human Total Ownership Cost) early in the life cycle will lead to schedule overruns, diminished system performance, inadequate training, and misaligned plans for manpower and personnel allocation. Cramer, Sudhoff, and Zivi (2011) posit that integrating survivability as a design objective early in the life cycle can benefit the design process. Assessing human capabilities during technology readiness level evaluation, according to Wallace, Bost, Thurber, and Hamburger (2007), can help the program avoid cost overruns.

The interaction between humans and the systems they use affects program success, as well as life-cycle costs. The documents from weapon systems acquisition programs, namely major defense acquisition programs (MDAP), contain a history of each program's system development life cycle, and this history indicates what considerations were involved in the system development life cycle. It follows then that HSI-related content in acquisition documents is interrelated with program success.

This article is essentially an investigative study or retrospective content analysis of MDAP documents. The author's goal is to present a sound argument that omitting HSI during weapon systems acquisition will coincide with acquisition life-cycle cost overruns, as well as schedule slippages and performance breaches. More specifically, this investigative study addresses the gap in knowledge among weapon systems acquisition, HSI, and acquisition life-cycle cost, performance, and schedule (Figure 1).

FIGURE 1. VENN DIAGRAM OF INTERRELATIONSHIPS AMONG WEAPON SYSTEMS, HSI, AND LIFE-CYCLE COST, PERFORMANCE, AND SCHEDULE



Problem Statement

Stakeholders, such as program managers and systems engineers, strive to mitigate unforeseen costs during the system development life cycle. One way to achieve this objective is to prioritize human considerations early in the system development life cycle. A program manager or systems engineer could predict program success using regression analysis of historical data. Program documents, such as Selected Acquisition Reports (SARs), provide a valuable source of historical data about weapon systems programs (Assidmi, Sarkani, & Mazzuchi, 2012; Bielecki & White, 2005; Birchler, Christle, & Groo, 2011). For purposes of this investigative study, logistic regression and HSI-related terminology in documents will be used to make predictions about program success.

Presence of HSI-related terminology is defined by the percentage of HSI-related words per document. *Program success* is defined by avoidance of cost overrun, avoidance of performance breach, or avoidance of schedule breach. Overall, the objective is to conduct a retrospective content analysis of MDAP documents as an approach by which to seek the presence of HSI-related terminology in weapon systems acquisition. This approach is designed to demonstrate that an earlier presence of HSI-related terminology will predict better outcomes for weapon systems acquisition programs with money saved, time saved, and good performance. A definitive research question that addresses the problem identified by this investigative study follows.

> *Does the percentage of HSI words within the document coincide with unforeseen cost overruns, performance breaches, and schedule slippages?*

Although the findings of this investigative study did not yield strongly predictive regression models, significant findings emerged that suggest schedule slippages and cost overruns may be associated with a reduction of HSI-related terminology. From the findings, the presence of terminology about human factors engineering, habitability, and survivability as well as manpower, personnel, and training suggests that a program will likely succeed. This finding corroborates the idea that a solution to the problem—specifically saving time, saving money, and improving performance—will be the inclusion of HSI-related content early in the weapon systems acquisition life cycle.

Data Collection

The data collection effort identified HSI-related terminology in each document, including HSI word percentages. Program success data were collected with regard to cost, schedule, and performance. Weapon systems acquisition programs, specifically MDAPs, were also identified. Additional data were collected to identify when each document was published with regard to its corresponding program's Milestone B.

HSI-Related Terminology

As shown in Table 1, the HSI-related terminology in this investigative study consisted of words that refer to the nine HSI domains defined by the Department of the Air Force (2014). Also included were the terms HSI and MANPRINT, which are synonymous (Drillings, 2014). It is helpful to note that HSI is defined differently among organizations. For example, Headquarters Department of the Army (2014) defined seven HSI domains:

1. manpower
2. personnel capabilities
3. training
4. human factors engineering
5. system safety
6. health hazards
7. soldier survivability

Department of the Navy (2009) defined seven slightly different HSI domains:

1. manpower
2. personnel
3. training
4. human factors engineering
5. environmental safety and occupational health
6. habitability
7. personnel survivability

Department of the Air Force (2014), however, defined nine versus seven HSI domains:

1. manpower
2. personnel
3. training
4. environment

5. safety
6. occupational health
7. human factors engineering
8. survivability
9. habitability

This investigative study refers to the most complete list of HSI domains, as identified by Department of the Air Force (Table 1).

TABLE 1. HSI-RELATED WORDS AND CORRESPONDING HSI DOMAINS

HSI Domain	HSI-Related Words
NA	HSI, Manpower and Personnel Integration (MANPRINT)
Human Factors Engineering	fatigue, human, people, perform, performance, performed, performing, performs, situational awareness, troops, usability, utility, workload
Habitability	habitability, shelter
Survivability	survivability
Environment	environment, environmental
Safety	protect, protected, protection, protective, safety, secure, security
Occupational Health	health
Manpower	interoperability, maintain, maintainability, maintained, maintainer, maintaining, maintains, maintenance, manpower, manned, manning, operability, operate, operated, operates, operating, operational
Personnel	infantry, manage, managed, management, manager, manages, managing, personnel, pilot, role, staff, warfighter, warrior
Training	instructor, train, trained, training

To indicate HSI-related terminology within each program document, data consisted of word percentages for each HSI-related word of interest for each of 546 program documents. These word percentages were calculated using word counts for each HSI-related word of interest and the total word count for each document. Table 2 shows the number of documents per program and the range of word counts per program.

TABLE 2. MAJOR DEFENSE ACQUISITION PROGRAMS		
Program Name	**Total Documents**	**Range of Word Counts**
Advanced Deployable System	7	504 to 1,237
DDG 1000 Zumwalt Class Destroyer	37	107 to 17,317
F-22 Raptor Advanced Tactical Fighter Aircraft	71	86 to 9,378
F-35 Joint Strike Fighter Aircraft	58	68 to 17,700
Ground/Air Task-Oriented Radar	6	228 to 3,807
EA-18G Growler Aircraft	35	89 to 39,656
F/A-18E/F Super Hornet	12	801 to 2,574
Joint Land Attack Cruise Missile Defense (JLACMD) Elevated Netted Sensor System	16	161 to 31,314
Joint Tactical Radio System	45	275 to 5,197
Littoral Combat Ship	27	73 to 64,661
Mine Resistant Ambush Protected Vehicle	48	115 to 51,790
P-8A Poseidon Multi-Mission Maritime Aircraft	22	178 to 31,658
Space Based Infrared System High	48	194 to 4,390
V-22 Osprey Joint Services Advanced Vertical Lift Aircraft	47	117 to 9,713
Vertical Take-off and Landing Tactical Unmanned Aerial Vehicle	16	150 to 2,721
Warfighter Information Network-Tactical	51	228 to 31,132

Data were collected from the 546 documents and entered into SPSS Statistics Version 22.0 for Windows. HSI words within the sampled documents ranged from zero to 2,262. The average number of HSI words was 42.60 (SD = 160.73). Total words for the sampled documents ranged from 68 to 64,661, and the total word count was 2,010.53 on average (SD = 5,109.40).

HSI-related words were separated into three categories (Table 3). Some overlap occurred among each of the HSI domains, and some words fit into more than one domain description. Typically, environmental, safety, and occupational health issues are grouped together and identified with the acronym *ESOH*, as are manpower, personnel, and training issues, which are identified as *MPT*. For this investigative study, these same groups were identified, thus the data included ESOH and MPT word percentages. Because the terms habitability and survivability generated a small quantity

of words, they were grouped together with Human Factors Engineering (HFE), along with the terms HSI and MANPRINT, thus the data included *HFE/Hab/Surv* word percentages.

TABLE 3. HSI-RELATED WORDS AND CORRESPONDING HSI CATEGORIES

HSI Category	HSI-Related Words
HFE/Hab/Surv	HSI, MANPRINT, fatigue, habitability, human, people, perform, performance, performed, performing, performs, shelter, situational awareness, survivability, troops, usability, utility, workload
ESOH	environment, environmental, health, protect, protected, protection, protective, safety, secure, security
MPT	infantry, instructor, interoperability, maintain, maintainability, maintained, maintainer, maintaining, maintains, maintenance, manage, managed, management, manager, manages, managing, manpower, manned, manning, operability, operate, operated, operates, operating, operational, personnel, pilot, role, staff, train, trained, training, warfighter, warrior

Success Metrics

Program success data were collected to investigate each MDAP's cost overruns, schedule slippages, and performance breaches. These success metrics were (a) SAR-identified cost breaches, (b) SAR-identified schedule breaches, (c) SAR-identified performance breaches, (d) GAO assessment indicating total program over budget, (e) GAO assessment indicating program unit cost increase, and (f) Weapon Book program amount spent went over budget. None of these six metrics had absolutely complete data because data were not available for each program for each fiscal year. To collect ample data, all six metrics were considered for this investigative study.

MDAPs

Several factors were considered in the selection of the sample of MDAPs analyzed in this study. Each program needed sufficient documentation for the HSI word analysis as well as cost, schedule, and performance data. Table 4 lists the 16 MDAPs alongside their common names. MDAP documents were collected between June 2013 and October 2014, primarily from the Defense Acquisition Management Information Retrieval (DAMIR) database (DAMIR, n.d.). Additional MDAP documents were collected from the Acquisition Decision Memoranda (ADM) Web site (ACQWeb) (Acquisition

Decision Memoranda, 2014). The objective was to acquire acquisition program documents that are consistent from program to program; the DAMIR database and ADM Web site made this possible.

TABLE 4. HSI-RELATED WORDS AND CORRESPONDING HSI DOMAINS

Program Name	Common Name
Advanced Deployable System	ADS
DDG 1000 Zumwalt Class Destroyer	DDG 1000
F-22 Raptor Advanced Tactical Fighter Aircraft	F-22
F-35 Joint Strike Fighter Aircraft	JSF
Ground/Air Task Oriented Radar	G/ATOR
EA-18G Growler Aircraft	EA-18G
F/A-18E/F Super Hornet	F/A-18E/F
Joint Land Attack Cruise Missile Defense (JLACMD) Elevated Netted Sensor System	JLENS
Joint Tactical Radio System	JTRS
Littoral Combat Ship	LCS
Mine Resistant Ambush Protected Vehicle	MRAP
P-8A Poseidon Multi-Mission Maritime Aircraft	P-8A
Space Based Infrared System High	SBIRS High
V-22 Osprey Joint Services Advanced Vertical Lift Aircraft	V-22
Vertical Take-off and Landing Tactical Unmanned Aerial Vehicle	VTUAV Fire Scout
Warfighter Information Network-Tactical	WIN-T

Note. If a program had any increments, then the increment was noted, and appropriate data for that increment were collected.

None of the MDAP documents identifying HSI-related terminology were used to obtain cost, schedule, or performance data. In addition to collecting MDAP documents, other sources of data were collected to identify program cost overruns, schedule slippages, and performance breaches (Table 5). Furthermore, none of the documents that were used for obtaining information about program cost overruns, schedule slippages, and performance breaches were used to obtain HSI data.

TABLE 5. BREACH DATA SOURCES

Breach Data Source and Description	Types of Breaches	Origin
Selected Acquisition Reports (SAR) indicate whether or not a program has experienced cost breach, schedule breach, or performance breach. Data indicating breaches were assigned 1s for breach occurrence and 0s for no breach.	cost overruns, schedule slippages, and performance breaches	DAMIR database (DAMIR, n.d.)
Government Accountability Office (GAO) assessments for major weapon programs report whether a program has gone over budget and whether a program's unit cost has increased. Data indicating that the total program had gone over budget were assigned 1s, as well as data indicating that the program's unit cost had increased; absences of these conditions were assigned 0s.	cost overruns	GAO Web site (GAO, 2014)
The Comptroller's Weapon Books report the Budget Request amounts that a program requested for a given fiscal year and later what the program actually spent during that fiscal year. A cost overrun can be determined from comparing what amount was requested and then what amount was actually spent. 1s were assigned to indicate that a program went over budget for the given fiscal year, and 0s were assigned in the absence of this condition.	cost overruns	Comptroller's Web site (Under Secretary of Defense Comptroller, 2014)

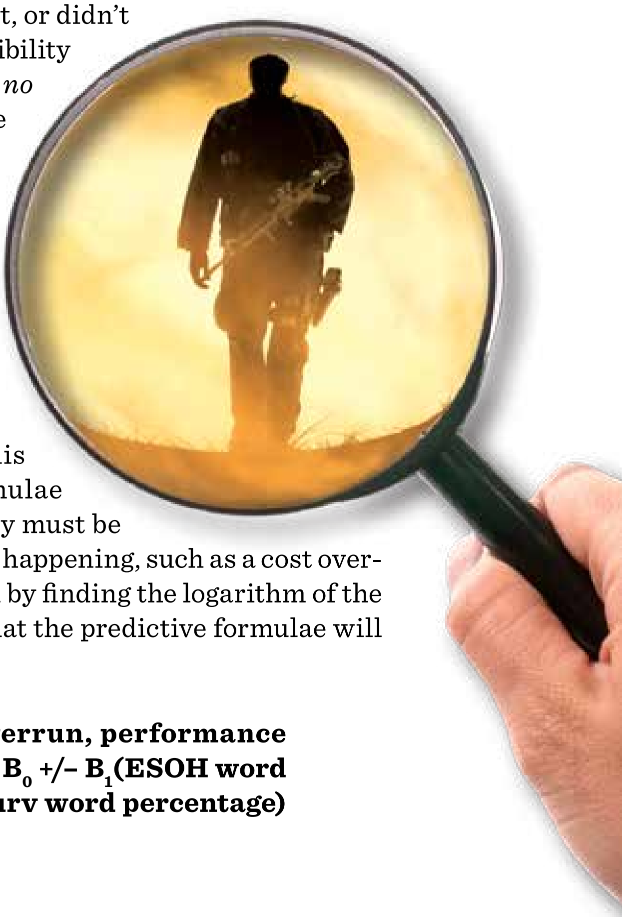
Experimental Design

Because the regression analysis was intended to measure six dependent variables, six analyses were conducted for each of the six dependent variables: (a) SAR cost breach, (b) SAR performance breach, (c) SAR schedule breach, (d) GAO total program over budget, (e) GAO program unit cost increase, and (f) Weapon Book amount spent over budget. Subcategories of HSI word percentage per MDAP document included (a) ESOH word percentage, (b) HFE/Hab/Surv word percentage, and (c) MPT word percentage. The independent variables were the subcategories of HSI word percentage per MDAP document.

Data Analysis

As shown in Table 5, qualitative breach data were categorized with 0s and 1s. When dependent variables are qualitative, a logistic regression equation can be used to create a model of the probability that the dependent variable's value will be either 0 or 1 (Chatterjee & Hadi, 2012). After the regression model has been created, the data are compared to the model to discover what ratio of the data was classified 0 or 1 correctly (Chatterjee & Hadi, 2012). Binary logistic regression, the data analysis method selected for this data set's interpretation, is a method for modeling probabilities when the outcome falls between 0 and 1.

Because each budget for each MDAP is unique from the budgets of other MDAPs, the numeric values for each budget would consist of different numbers that cannot be directly compared. To assess the data, one may ask the question, "Did an MDAP go over budget, or didn't it?" Answering this question opens the possibility to make the data dichotomous with 0s for *no* and 1s for *yes*. These dichotomous data are qualitative because they yield a qualitative value, such as *good* or *bad* (Chatterjee & Hadi, 2012). In this manner, data regarding whether or not there was a breach can be assigned (categorized) 0s and 1s, and the appropriate statistical method is binary logistic regression.



Shown here is the model for the predictive formulae that were the outcome of this study's analysis. Because predictive formulae from logistic regression are nonlinear, they must be transformed. The probability of something happening, such as a cost overrun, is the odds ratio. The logit is identified by finding the logarithm of the odds ratio. This transformation ensures that the predictive formulae will be linear (Chatterjee & Hadi, 2012).

logit[Pr(Y=Unforeseen cost overrun, performance breach, or schedule slippage)] = B_0 +/– B_1(ESOH word percentage) +/– B_2(HFE/Hab/Surv word percentage) +/– B_3(MPT word percentage)

Results

To examine the hypothesis, a series of binary logistic regressions was conducted. Due to the exploratory nature of this investigative study, an alpha level of 0.10 was employed for assessment of statistical significance. The hypothesis is shown here.

> *The percentage of HSI words within the document will coincide with unforeseen cost overruns, performance breaches, and schedule slippages.*

Results of the six regression analyses are presented in Table 6, while regression coefficients are presented in Table 7. Four of the six regressions yielded significant models. SAR schedule breach, GAO total program over budget, GAO program unit cost increase, and Weapon Book amount spent over budget were associated with either ESOH word percentage, HFE/Hab/Surv word percentage, or MPT word percentage. These four regressions were further analyzed to assess the hypothesis.

TABLE 6. MODEL FIT FOR SIX BINARY LOGISTIC REGRESSION ANALYSES			
Dependent Variable	**$\chi^2(7)$**	***p***	**Nagelkerke R^2**
1. SAR cost breach	9.15	.242	.03
2. SAR performance breach	5.90	.552	.07
3. SAR schedule breach*	20.21	.005	.06
4. GAO total program over budget*	28.00	< .001	.13
5. GAO program unit cost increase*	22.29	.002	.12
6. Weapon Book amount spent over budget *	23.83	.001	.14

Note. An asterisk (*) indicates significance at the $p < .10$ level.

TABLE 7. MODEL COEFFICIENT DETAILS FOR BINARY LOGISTIC REGRESSIONS					
Regression	***B***	***SE***	***Wald***	***p***	***O.R.***
SAR schedule breach †					
MPT word percentage	-0.74	0.34	4.75	.029	0.48
GAO total program over budget †					
MPT word percentage	-0.98	0.59	2.78	.095	0.38
GAO program unit cost increase †					
MPT word percentage	-1.05	0.51	4.23	.040	0.35
Weapon Book amount spent over budget †					
ESOH word percentage	5.23	2.86	3.35	.067	187.23
HFE/Hab/Surv word percentage	-4.90	1.77	7.64	.006	0.01
MPT word percentage	1.06	0.64	2.74	.098	2.87

Note. A dagger (†) indicates model significance at the $p < .10$ level.

To examine the hypothesis, the three predictors (ESOH word percentage, HFE/Hab/Surv word percentage, and MPT word percentage) of the four significant models were examined (Table 6). Model coefficients are presented in Table 7. For SAR schedule breach, MPT word percentage was a significant predictor ($B = -0.74$, $p = .029$, $OR = 0.48$), suggesting that as the percentage of MPT words increased, the likelihood of a SAR schedule breach decreased.

For GAO total program over budget, MPT word percentage was a significant predictor (B = -0.98, p = .095, OR = 0.38), suggesting that as the percentage of MPT words increased, the likelihood of a GAO total program over budget decreased. For GAO program unit cost increase, MPT word percentage was a significant predictor (B = -1.05, p = .040, OR = 0.35), suggesting that as the percentage of MPT words increased, the likelihood decreased for a GAO program unit cost increase. For Weapon Book amount spent over budget, ESOH word percentage was a significant predictor (B = 5.23, p = .067, OR = 187.23), suggesting that as the percentage of ESOH words increased, the likelihood of a Weapon Book amount spent over budget increased. Also for Weapon Book amount spent over budget, HFE/Hab/Surv word percentage was a significant predictor (B = -4.90, p = .006, OR = 0.01), suggesting that as the percentage of HFE/Hab/Surv words increased, the likelihood of a Weapon Book amount spent over budget decreased. Last, MPT word percentage was a significant predictor of Weapon Book amount spent over budget (B = 1.06, p = .098, OR = 2.87), suggesting that as the percentage of MPT words increased, the likelihood of a Weapon Book amount spent over budget also increased.

Predictive Equations

For each of the four significant models, each regression was solved to provide a predictive formula for the relationship between HSI word percentage outcomes and the variables of interest to Hypothesis One. Each of these predictive formulae consider ESOH word percentage, HFE/Hab/Surv word percentage, or MPT word percentage as subcategories of HSI word percentage. The first significantly predictive model suggested that MPT word percentage was the only factor that made a unique contribution to the prediction of SAR schedule breaches. Increased percentage of MPT words contributed to a lower likelihood of SAR schedule breaches. This model resulted in the final equation shown here.

logit[Pr(Y=SAR schedule breach)] = 0.06 – 0.74(MPT word percentage)

The second significantly predictive model suggested that MPT word percentage was again the only factor that made a unique contribution to the prediction of GAO total program over budget cost overruns. Increased percentage of MPT words contributed to a lower likelihood of GAO total program over budget cost overruns. This model resulted in the final equation shown here.

logit[Pr(Y=GAO total program over budget cost overrun)] = 3.20 – 0.98(MPT word percentage)

The third significantly predictive model suggested that the percentage of MPT words was again the only factor that made a unique contribution to the prediction of GAO program unit cost increases. Increased percentage of MPT words contributed to a lower likelihood of GAO program unit cost increases. This model resulted in the final equation shown here.

logit[Pr(Y=GAO program unit cost increase)] = 2.61 – 1.05(MPT word percentage)

The fourth significantly predictive model suggested that ESOH word percentage, HFE/Hab/Surv word percentage, and MPT word percentage all made a unique contribution to the prediction of Weapon Book amount spent over budget cost overruns. An increased percentage of ESOH words or MPT words contributed to a greater likelihood of Weapon Book amount spent over budget cost overruns, while an increased percentage of HFE/Hab/Surv words contributed to a lower likelihood of cost overruns. This model resulted in the final equation shown here.

logit[Pr(Y=Weapon Book amount spent over budget cost overrun)] = -0.61 + 5.23(ESOH word percentage) – 4.90(HFE/Hab/Surv word percentage) + 1.06(MPT word percentage)

> ***Cost overruns identified by Weapon Books are more affected by the presence of HSI-related terminology than are total program cost overruns identified by GAO assessments, program unit cost overruns identified by GAO assessments, and schedule breaches identified by SARs.***

Analysis of the hypothesis with all predictor variables yielded the Nagelkerke R^2 values for the four significant models: SAR schedule breach, $R^2 = 0.06$; GAO total program over budget, $R^2 = 0.13$; GAO program unit cost increase, $R^2 = 0.12$; and Weapon Book amount spent over budget, $R^2 = 0.14$. Therefore, cost overruns identified by Weapon Books are more affected by

the presence of HSI-related terminology than are total program cost overruns identified by GAO assessments, program unit cost overruns identified by GAO assessments, and schedule breaches identified by SARs. However, the Nagelkerke R^2 value is low for each of these four outcomes, thus rendering little predictive power.

Model Sensitivity and Specificity

Sensitivity and specificity were examined for each model using classification plots. Each plot describes the percentage of correct classifications for a predictive equation. Four models indicated a significant predictive ability. Therefore, the four models were examined for their ability to correctly classify cases. Results of the classification tables are presented in Table 8.

TABLE 8. CLASSIFICATION TABLES FOR EACH BINARY LOGISTIC REGRESSION

Dependent Variable	Observed	Predicted		Total Documents	Percentage Correct	Overall Percentage
		No	Yes			
SAR Cost Breach	No	352	0		100%	
	Yes	156	0	508	0%	69%
SAR Performance Breach	No	500	0		100%	
	Yes	9	0	509	0%	98%
SAR Schedule Breach*	No	349	6		98%	
	Yes	141	5	495	3%	71%
GAO Total Program over Budget*	No	16	78		17%	
	Yes	10	188	292	95%	70%
GAO Program Unit Cost Increase*	No	4	53		7%	
	Yes	2	215	274	99%	80%
Weapon Book Amount Spent over Budget*	No	180	4		98%	
	Yes	53	11	248	17%	77%

Note. An asterisk (*) indicates significance at the p < .10 level.

As shown in Table 9, sensitivity and specificity were also examined using classification plots for each of the 16 MDAPs. Data were separated by MDAP, and 16 models were examined. Nine of the 16 models indicated a significant predictive ability and were examined for their ability to correctly classify cases.

TABLE 9. CLASSIFICATION TABLES FOR EACH MAJOR DEFENSE ACQUISITION PROGRAM

MDAP	Observed	Predicted		Total Documents	Percentage Correct	Overall Percentage
		No	Yes			
DDG 1000 Zumwalt Class Destroyer	No	1	6		14%	
	Yes	2	28	37	93%	78%
EA-18G Growler Aircraft	No	10	6		63%	
	Yes	0	19	35	100%	83%
F/A-18E/F Super Hornet	No	8	1		89%	
	Yes	1	2	12	67%	83%
F-22 Raptor Advanced Tactical Fighter Aircraft*	No	6	14		30%	
	Yes	0	51	71	100%	80%
Ground/ Air Task Oriented Radar*	No	3	0		100%	
	Yes	0	3	6	100%	100%
Joint Land Attack Cruise Missile Defense (JLACMD) Elevated Netted Sensor System*	No	10	0		100%	
	Yes	0	6	16	100%	100%
F-35 Joint Strike Fighter Aircraft	No	1	5		17%	
	Yes	0	52	58	100%	91%

TABLE 9. CLASSIFICATION TABLES FOR EACH MAJOR DEFENSE ACQUISITION PROGRAM (CONTINUED)

MDAP	Observed	Predicted No	Predicted Yes	Total Documents	Percentage Correct	Overall Percentage
Joint Tactical Radio System*	No	11	5		69%	
	Yes	0	29	45	100%	89%
Littoral Combat Ship*	No	9	4		69%	
	Yes	1	13	27	93%	82%
Mine Resistant Ambush Protected Vehicle	No	11	11		50%	
	Yes	10	16	48	62%	56%
P-8A Poseidon Multi-Mission Maritime Aircraft	No	12	2		86%	
	Yes	8	0	22	0%	55%
Space Based Infrared System High*	No	5	4		56%	
	Yes	0	39	48	100%	92%
V-22 Osprey Joint Services Advanced Vertical*	No	10	6		63%	
	Yes	5	26	47	84%	77%
Vertical Take-off and Landing Tactical Unmanned Aerial Vehicle	No	3	5		38%	
	Yes	4	4	16	50%	44%
Warfighter Information Network-Tactical*	No	15	11		58%	
	Yes	6	19	51	76%	67%

Note. An asterisk (*) indicates significance at the $p < .10$ level. An additional dependent variable was defined from the six dependent variables. If there was any breach indicated by any of the dependent variables, then a value of 1 was assigned to this new variable. If none of the dependent variables indicated any breach, then a value of 0 was assigned to this new variable. Because the Advanced Deployable System (ADS) had no breaches, as indicated by the six dependent variables, the new variable had a value of 0 for each case (each program document). Because there was no variance, binary logistic regression analysis could not be applied to the data for ADS. There were seven program documents for ADS, and those seven cases have been omitted from this table.

Discussion

In reference to Hypothesis One, the presence of HSI-related words in an MDAP document may be associated with whether or not a program will experience a schedule breach or a cost overrun. First, assessing individual predictors from three significant regression models suggests that a schedule breach identified by a SAR or a cost overrun identified by GAO assessment of total program cost or program unit cost is less likely to occur when more MPT words are present. Second, assessing individual predictors from another significant regression model suggests that a cost overrun identified from Weapon Book budget data is more likely to occur when more ESOH or MPT words are present. However, a cost overrun is less likely to occur when more HFE/Hab/Surv words are present. Therefore, considering SAR data and GAO assessment data, the presence of terminology about MPT in a weapon system's acquisition program documents suggests that the program might not experience a schedule slippage or cost overrun. Considering Weapon Book budget data, the presence of terminology about MPT in a weapon system's acquisition program documents suggests that the program will experience a cost overrun. Also regarding Weapon Book budget data, the presence of terminology about ESOH in a weapon system's acquisition program documents suggests that the program will experience cost overruns, whereas the presence of terminology about HFE/Hab/Surv suggests that the program might not experience a cost overrun.

During the acquisition life cycle, program success can be affected by various efforts conducted by program managers and systems engineers. As shown in Figure 2, three milestones within the *Analysis of Alternatives (AoA)* occur prior to Milestone A, where a group of concepts are identified and compared among one another (Department of Defense [DoD], 2015). Milestone A is when the *Risk Reduction Decision* is made, whereby a specific concept is selected for further development and resources are committed to the maturation of relevant technology (p. 7). Milestone B is when the *Development*

Decision is made, and contracts are awarded for producing and testing the concept (p. 7). Milestone C is when *Low-Rate Initial Production* of the concept begins (p. 7).

FIGURE 2. ACQUISITION LIFE CYCLE

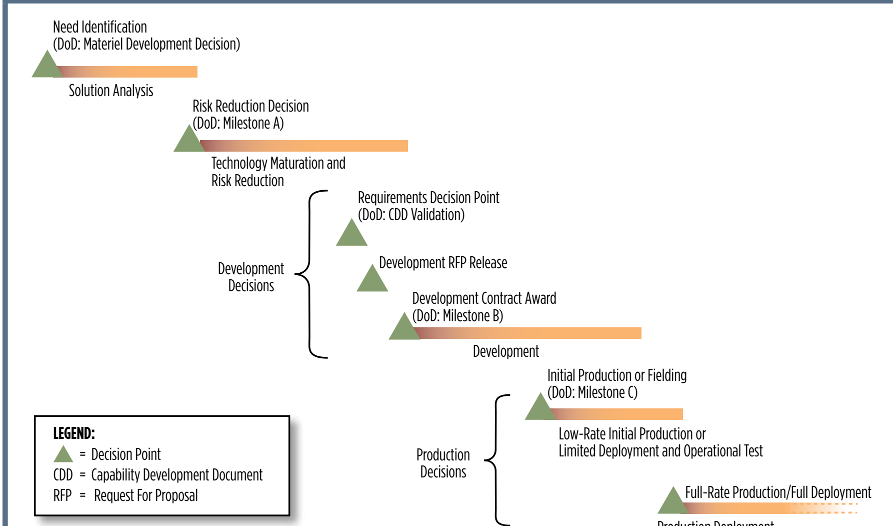


Figure 2 illustrates the sequence of decision events in a generic program. It is not intended to reflect the time dedicated to associated phase activity.

Meanwhile, a program's cost estimation can be impacted during the time period leading up to Milestone B. By Milestone B, 70 percent of a system's life-cycle cost will have been determined by design decisions regarding the program's features and efforts (Deitz, Eveleigh, Holzer, & Sarkani, 2013; General Accounting Office, 1981; Zimmerman, Butler, Gray, & Rosenberg, 1984). After errors have been made at the Milestone B decision point, repairing the errors or compensating for them costs between three and 10 times more than the cost of the original, erroneous efforts (Deitz et al., 2013).

Program managers and systems engineers can apply the observations from this investigative study to their understanding of human considerations and what impact human considerations have on the development of a given program. Systems engineering includes HSI, and HSI can be incorporated into the content of program documents, such as the requirements documents. Requirements definition is one facet of SE, which is the interdisciplinary approach for developing systems (INCOSE, 2012). MDAPs employ SE to conduct weapon systems acquisition for the DoD. To minimize weapon systems acquisition costs, the DoD created the Better Buying Power mandate,

which has identified some focus areas with appropriate initiatives, such as (a) eliminating requirements that lead to nonvalue-added processes, (b) improving how requirements are defined, and (c) inhibiting requirements from changing over time, in other words, requirements creep (DoD, n.d.).

Conclusions

The data for this investigative study were representative of different customers within the U.S. Government (Air Force, Army, DoD, Marine Corps, and Navy) and of different types of weapon systems (aircraft, communications network, ground vehicle, ship, etc.), which helps ensure validity of the findings among customers and weapon systems. This investigative study looked back at existing MDAP documents in a retrospective content analysis as a means to look forward for program success. Considering how many MDAPs exist, the sample size was relatively small. However, the value of this study is that it has revealed a trend that HSI practitioners already suspected and that can be examined further by investigating more programs with more documents. Exposing trends by looking at historical data, such as how HSI impacts weapon systems acquisition, is informative for planning and developing future systems.

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We would like to express our appreciation to all of the subject matter experts who volunteered to participate in the *Defense Acquisition Research Journal* peer review process. The assistance of these individuals provided impartial evaluation of the articles published during the 2015 print year. We would also like to acknowledge those referees who wished to remain anonymous. Your continued support is greatly appreciated, and we look forward to working with many of you again in print year 2016.

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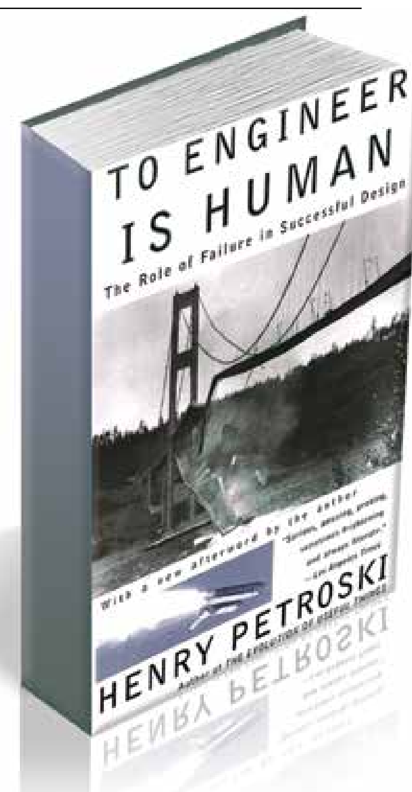
Featured Book

To Engineer is Human: The Role of Failure in Successful Design



Author: Henry Petroski
Publisher: Vintage
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Softcover, 272 pages, http://www.amazon.com/To-Engineer-Is-Human-Successful/dp/0679734163
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ISBN-13: 978-0679734161
Reviewed by:
Henry Petroski, Professor of Civil Engineering and History, Duke University

Review:

This book has its origins in the basic question: What is engineering? It sets forth the premise that understanding *failure* is essential to understanding and achieving success in engineering. Fundamentally, engineering is figuring out how things work, solving problems, and finding practical uses and ways of doing things that have not been done before. Successful engineers properly anticipate how things can fail, and design accordingly. Case studies of past failures thus provide invaluable information for the design of future successes.

Conversely, designs based on the extrapolation of successful experience alone can lead to failure, because latent design features that were not important in earlier systems can become overlooked design flaws that dominate the behavior of more complex systems that evolve over time. This paradox is explored in *To Engineer is Human* in the context of historical case studies, which provide hard data to test the hypotheses put forward. Among the historical data points are the repeated and recurrent failures of suspension bridges, which from the 1850s through the 1930s evolved from John Roebling's enormous successes—culminating in the Brooklyn Bridge—to structures that oscillated in the wind and, in the case of the Tacoma Narrows Bridge, twisted itself apart and collapsed in 1940. Lessons learned from these cases and others are generalized to apply across a broad spectrum of engineering structures and complex systems. They also help explain why failures continue to occur, even as technology advances.

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Defense ARJ Guidelines FOR CONTRIBUTORS

The *Defense Acquisition Research Journal (ARJ)* is a scholarly peer-reviewed journal published by the Defense Acquisition University (DAU). All submissions receive a blind review to ensure impartial evaluation.

IN GENERAL

We welcome submissions from anyone involved in the defense acquisition process. *Defense acquisition* is defined as the conceptualization, initiation, design, development, testing, contracting, production, deployment, logistics support, modification, and disposal of weapons and other systems, supplies, or services needed for a nation's defense and security, or intended for use to support military missions.

Research involves the creation of new knowledge. This generally requires using material from primary sources, including program documents, policy papers, memoranda, surveys, interviews, etc. Articles are characterized by a systematic inquiry into a subject to discover/revise facts or theories with the possibility of influencing the development of acquisition policy and/or process.

We encourage prospective writers to coauthor, adding depth to manuscripts. It is recommended that a mentor be selected who has been previously published or has expertise in the manuscript's subject. Authors should be familiar with the style and format of previous *Defense ARJs* and adhere to the use of endnotes versus footnotes (refrain from using the electronic embedding of footnotes), formatting of reference lists, and the use of designated style guides. *It is also the responsibility of the corresponding author to furnish a government agency/employer clearance with each submission.*

MANUSCRIPTS

Manuscripts should reflect research of empirically supported experience in one or more of the areas of acquisition discussed above. Empirical research findings are based on acquired knowledge and experience versus results founded on theory and belief. Critical characteristics of empirical research articles:

- clearly state the question,
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- describe the research instrument,
- describe the limitations of the research,
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Research articles may be published either in print and online, or as a Web-only version. Articles that are 4,500 words or less (excluding abstracts, references, and endnotes) will be considered for print as well as Web publication. Articles between 4,500 and 10,000 words will be considered for Web-only publication, with an abstract (150 words or less) included in the print version of the *Defense ARJ*. In no case should article submissions exceed 10,000 words.

Book Reviews

Defense ARJ readers are encouraged to submit reviews of books they believe should be required reading for the defense acquisition professional. The reviews should be 400 words or fewer describing the book and its major ideas, and explaining why it is relevant to defense acquisition. In general, book reviews should reflect specific in-depth knowledge and understanding that is uniquely applicable to the acquisition and life cycle of large complex defense systems and services.

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Please submit your manuscript with references in APA format (author-date-page number form of citation) as outlined in the *Publication Manual of the American Psychological Association* (6th Edition). For all other style questions, please refer to the *Chicago Manual of Style* (16th Edition).

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Pages should be double-spaced and organized in the following order: title page (titles, 12 words or less), abstract (150 words or less to conform with formatting and layout requirements of the publication), two-line summary, list of keywords (five words or less), body of the paper, reference list (only include works cited in the paper), author's note or acknowledgments (if applicable), and figures or tables (if any).

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    - Two-line summary
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Defense ARJ
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Author Deadline	Issue
July	January
November	April
January	July
April	October

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Contributors may direct their questions to the Managing Editor, *Defense ARJ*, at the address shown below, or by calling 703-805-3801 (fax: 703-805-2917), or via the Internet at norene.fagan-blanch@dau.mil.

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